



**BARTLETT SCHOOL OF GRADUATE STUDIES**

**EVALUATION OF THE POTENTIAL OF SOLAR  
ENERGY TECHNOLOGY IN THE PUBLIC  
LIBRARY OF MEDELLÍN, COLOMBIA**

By,

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**15 September 2006**

**A Dissertation submitted in part fulfilment of the  
degree of Master of Science Built Environment:  
Environmental Design and Engineering**

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## ABSTRACT

The environmental benefits of a solar plant in Medellín, Colombia, were analyzed using a model that takes into account the energy and environmental costs of electricity generation. The model is based on the energy costs, which are derived from the historical data of the city of Medellín (1980-1990) and a 17% discount rate (see page 11). The high environmental potential of energy was analyzed using a 17% discount rate for the environmental benefits (see page 11) and a 17% discount rate for the environmental costs (see page 11). The results show that the environmental benefits of a solar plant are higher than the environmental costs.

The model was used to analyze the environmental benefits of a solar plant in Medellín, Colombia, using a 17% discount rate. The results show that the environmental benefits of a solar plant are higher than the environmental costs. The model was used to analyze the environmental benefits of a solar plant in Medellín, Colombia, using a 17% discount rate. The results show that the environmental benefits of a solar plant are higher than the environmental costs.

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## Abstract



## ABSTRACT

The investigation is based on a public library in Medellín, Colombia. It is a city of over 3 million inhabitants, where the demand for energy is rapidly increasing and according to predictions, is likely to exceed the existing supply, which comes primarily from hydroelectric dams (80.94%), thermoelectric (18.33%) and a 0.73% from others (see graph 11). This high dependency on sources of energy whose increment would have a high impact on the environment (hydroelectricity) or that emit substantial amounts of CO<sub>2</sub> emissions (thermoelectric) proves the need for alternative sources of energy.

Taking into account that Medellín is located near the equator (6.22°N) and has a high and constant solar radiation, the use of solar energy seems to be a feasible solution to cover the demand of a city whose population will increase in the next 9 years in 3'800,000. The increase in energy consumption is not only due to an increase in the population but also to a greater demand for more comfortable living conditions. That will create a demand for more equipment, such as air-conditioning units, which use large amounts of energy.

This public library was built in 2004, taking advantage of the available passive solar energy. Through the use of specific design strategies in the building, the light energy from the sun can be harnessed and preventing overheating without the use of air-conditioning units can be achieved. The library was chosen as a case study in order to show that besides the use of passive solar strategies, used in the building design, it is possible to use the solar energy in an active way.

In order to use active solar energy, it was necessary to evaluate the viability of introducing photovoltaic panels and a solar cooling system, generating electricity and improving the comfort conditions inside the building respectively. To achieve this, a virtual model of the building was run using the computer programs EPlus and SACE.

Firstly, the energy consumption of the building was calculated using the program Eplus. Then, using the same program, the amount of energy produced by the photovoltaic panels was calculated. In order to determine the solar cooling, the computer program SACE was used to find the Solar Fraction Cooling. This figure shows the area that should be covered by the solar panels to supply the cooling of the building. In addition, Solar Fraction Cooling indicates the efficiency of the solar cooling system in relation with the heat storage capacity of the collector.

A cost benefit analysis was then carried out comparing the photovoltaic panels and solar cooling systems with the existing energy generation mechanisms. This cost benefit analysis took into account the economic, environmental, and social implications of solar energy generation in the context of Medellín.

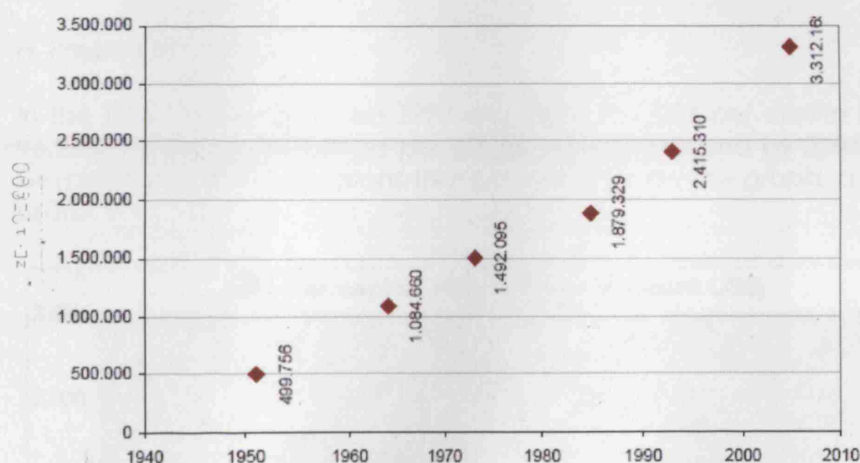
# 1. INTRODUCTION: Energy demand and supply

## 1. Energy demand and supply

### 1.1. Demand

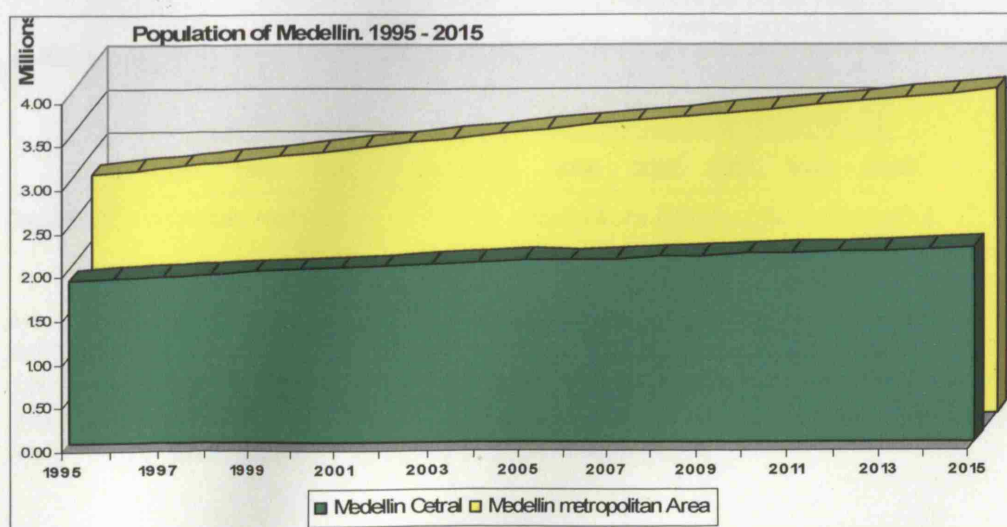
#### 1.1.1. Population

According to DANE's (Departamento Administrativo de Planeacion Nacional) 2003 census, the country has a population of 44,531,434, the greatest proportion of which is found in urban centres (72%). One of these urban centres is Medellín, Colombia's second city. The population of greater Medellín was 499,756 according to the 1951 census, and according to the last census (2005) the population was 3,312,165, representing an increase of 662.8% (to 1 d.p.) over the last 54 years. This population corresponds to greater Medellín (Area Metropolitana<sup>1</sup>), the city itself and the towns within its proximity, determined by Medellín's local authorities. These towns are: Barbosa, Bello, Caldas, Copacabana, Envigado, Girardota, Itagui, La Estrella and Sabaneta.



<sup>1</sup> Ordenanza No. 34 de Noviembre 27 de 1980; Medellín; Barbosa; Bello; Caldas; Copacabana; Envigado; Girardota; Itagui; La Estrella; Sabaneta

**Graph 01.** Current population of the greater Medellín. Census from 1951 to 2005.<sup>2</sup>



**Graph 02.** Projections of Medellín's population from 1995 to 2015.<sup>3</sup>

<sup>1</sup> Greater Medellín or 'Area Metropolitana': It is referred to the area within the following towns: Medellín, Barbosa, Bello, Caldas, Copacabana, Envigado, Girardota, Itagui, La Estrella and Sabaneta.

<sup>2</sup> DANE (Departamento Administrativo Nacional de Estadística). National Statistics Department.  
[http://www.dane.gov.co/files/censo2005/resultados\\_de\\_5pam.pdf](http://www.dane.gov.co/files/censo2005/resultados_de_5pam.pdf)



According to graph 02, the population will continue growing; it predicts that by 2015 it will be 3,800,000. It is important to point out that the growth accounts for Greater Medellín and not just Medellín itself, as shown by the graph above, which shows a steady line for Medellín's population. It means that the most significant population growth will occur in the towns that are part of Greater Medellín, with an increase of approximately 25% over the following 10 years.

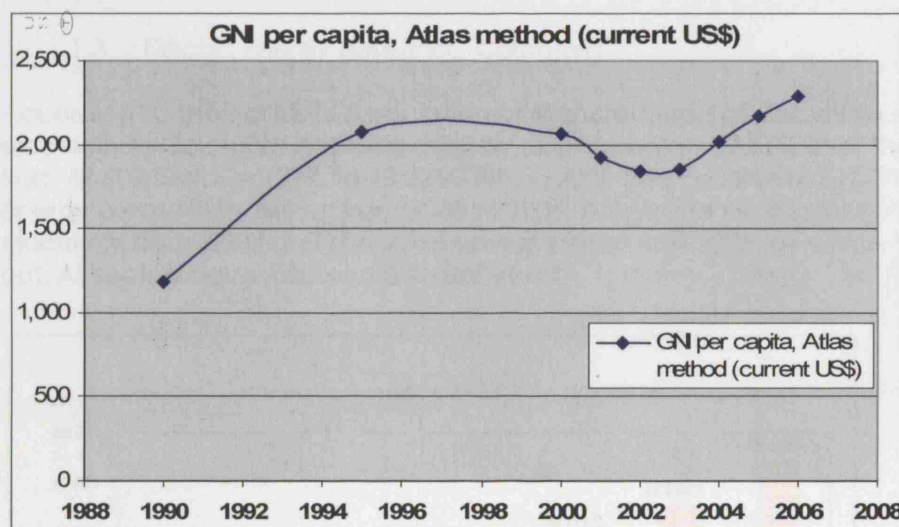
### 1.1.2. Socio-economic level:

In order to explain the standard of living conditions of Colombia, the following macroeconomic factors have been considered:

Gross Net Income per capita and the proportion of the population living below Poverty Line up to the present day and the Gross Domestic Product per capita, Investment level and Employment rate that have been projected up till the year 2019.

#### a. Present Situation:

In the time period between 1990 and 2006, the GNI per capita increased by approximately 96.21%. In 1990, the income per capita was \$1,190 and by 2006 it had increased to \$2,290. Despite the slight fluctuations that can be seen on the graph, a clear upward trend can be seen.



**Graph 03.** Colombia Net Gross Income per capita from 1988 to 2008 (projection).

Another factor that suggests that the standard of the living is increasing is the fact that the proportion of the population living below the poverty line is decreasing. This proportion decreased by 39.4% from 1900 to 2004, according to the National Planning Department (DNP)<sup>4</sup>. In 1900, the proportion of the population living below the poverty line was 92%, by 1950 it had decreased to 85% and in 2004, it was 52.6%.

<sup>3</sup> DANE (Departamento Administrativo de Planeación Nacional)  
[http://www.dane.gov.co/files/censo2005/resultados\\_am\\_municipios.pdf](http://www.dane.gov.co/files/censo2005/resultados_am_municipios.pdf)

<sup>4</sup> DNP is the National Planning Department. (Departamento Administrativo de Planeación Nacional)

## b. Projections up to 2019:

According to the above source, the Gross Domestic Product per capita is expected to rise by 70% by 2019. Other factors that show this positive trend are the increase in the level of investment, expected to rise threefold by 2019 and the employment rate that is expected to increase by 60% over the same period (see the table below).

FACTORS	2005	2019	Number of times increase	Annual Grow rate
GDP (millions of pesos 1994)	86.706.737	179.831.476	2,1	5,3%
GDP per Capita (US \$ from 2004)	2.208	3.811	1,7	3,9%
Level of Investment (millions of pesos 1994)	14.826.469	44.836.611	3,0	8,6%
Employment rate (Number of people working)	18.024.240	29.036.031	1,6	3,4%
Population	46.039.144	55.385.661	1,2	1,3%

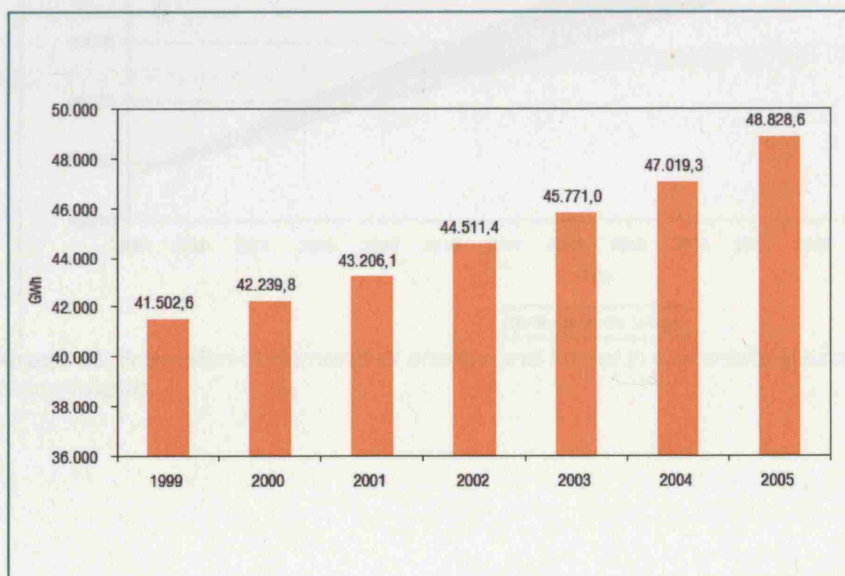
**Table 01.** Colombian macroeconomic factors (2005- 2019). Source DNP

As Medellín has been following the national trend, the above factors will be considered generally applicable to this city.

All this suggests a higher standard of living in the future, which in turn will determine an additional national demand of energy.

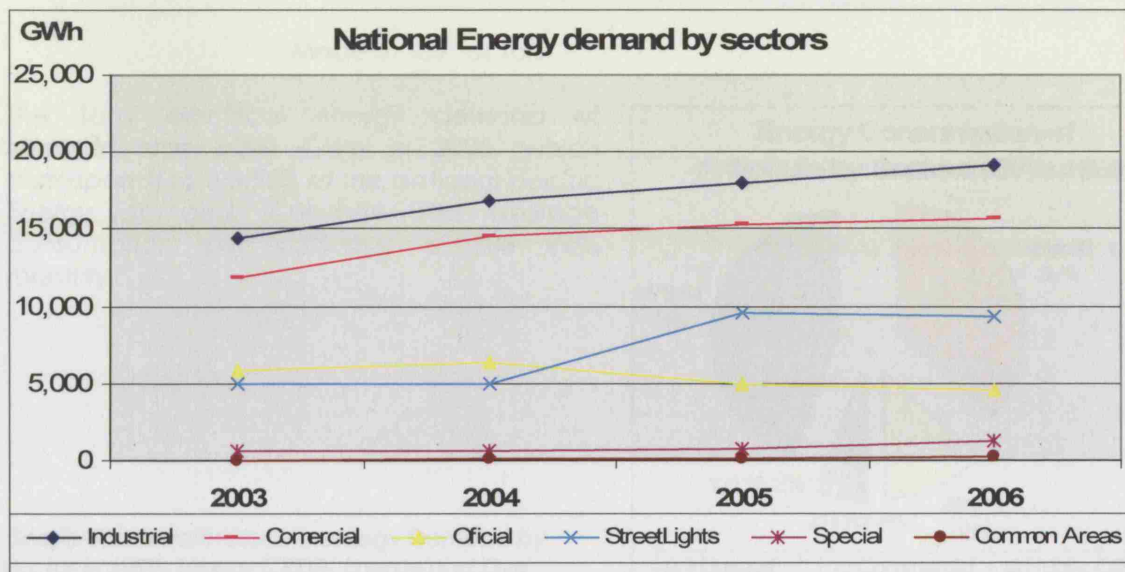
## 1.1.3. Electric Energy demand: Colombia

According to The National Association of Manufacturers of Colombia ANDI<sup>5</sup>, the demand for electricity in Colombia has increased by approximately 17.65% over the last six years. It went from 41,502 GWh, in 1999, to 48,828 GWh, in 2005 (see graph below). The graph 05 shows the energy demand by sector from 2003 to 2006. It illustrates an increase in the demand for electricity since 2003 and shows an upward trend until 2005, by which time it starts to plateau out. All sectors have followed a similar trend.



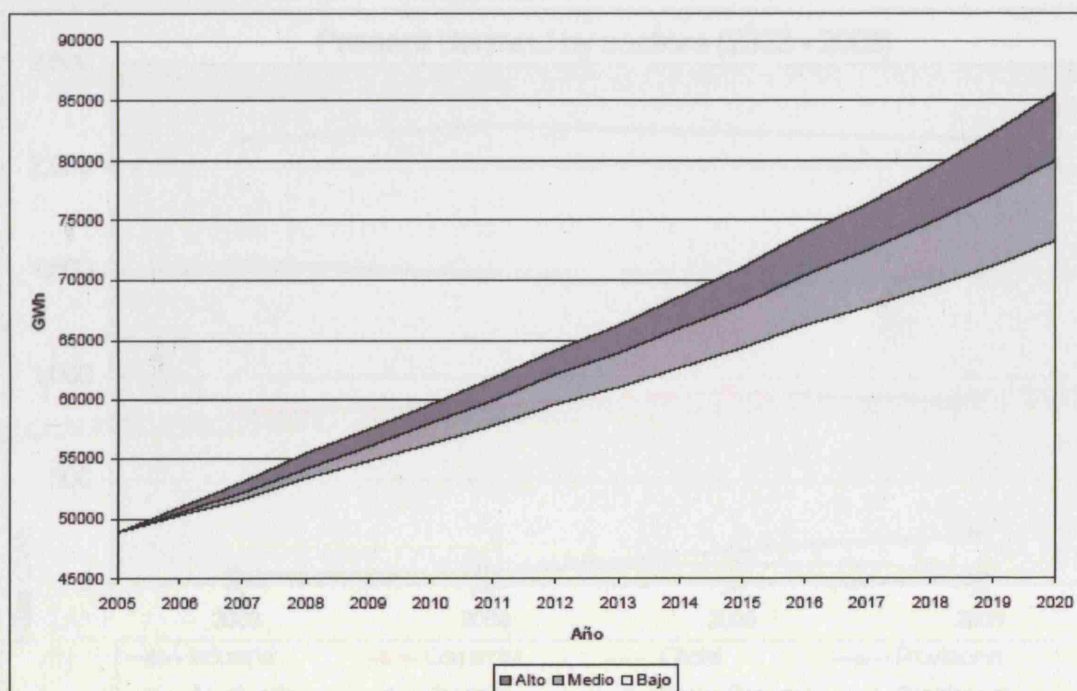
**Graph 04.** National evolution of the demand of electricity 1999 to 2005.

<sup>5</sup> ANDI. The National Association of Manufacturers of Colombia (Asociacion de Empresarios de Colombia). <http://www.andi.com.co>



Graph 05. National Electric energy Demand by sector. Source CREG<sup>6</sup>

It is projected that the national demand for electricity in 2020 will be 85,613 GWh, that would represent a 75% increase over 15 years, as shown by the below graph of the DNP.



Graph 06. Projection of demand of energy and Power in Colombia. Source DNP (National Planning Department)

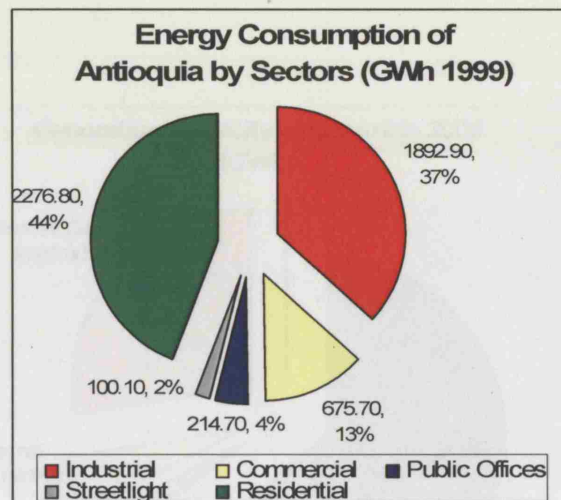
<sup>6</sup> CREG: Energy and Gas Regulatory Commission (Comisión de Regulación de Energía y Gas). [www.creg.gov.co](http://www.creg.gov.co)



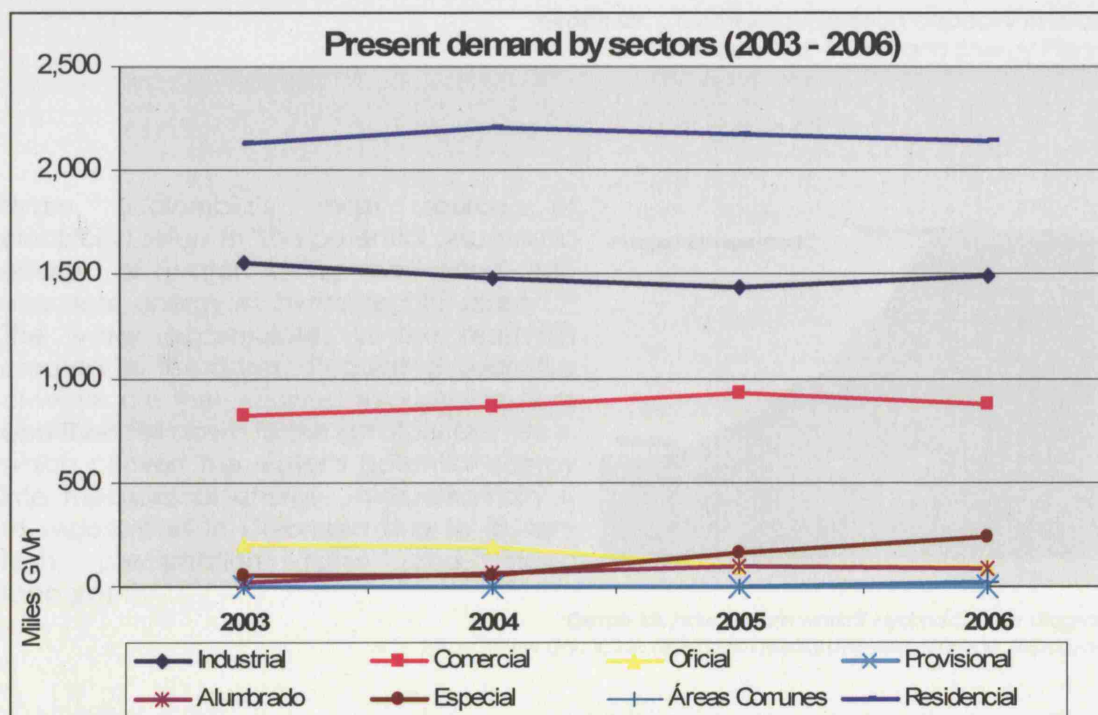
## Medellín (by sectors)

The total electrical energy demand of Medellín was 3,200 GWh in 2005, which corresponds to a 6.55% of the National Electric Energy demand. Currently, the average consumption per costumer is 286 kWh monthly.<sup>7</sup>

**Graph 07.** Medellín Electric energy Demand by sector in 1999. Source CREG( Energy and Gas Regulatory Commission)



The graph below shows the present electricity demand of Medellín by sectors. It shows that the sector with the highest demand is the residential one with 1,494 GWh in 2005.



**Graph 08.** Medellín Electric energy Demand by sector from 2003 to 2006. Source CREG( Energy and Gas Regulatory Commission)

By 2020 it is predicted that Medellín's total demand for electricity will be 5,607GWh. According to the projections it is going to increase by 75% in 15 years, in line with the national predictions.

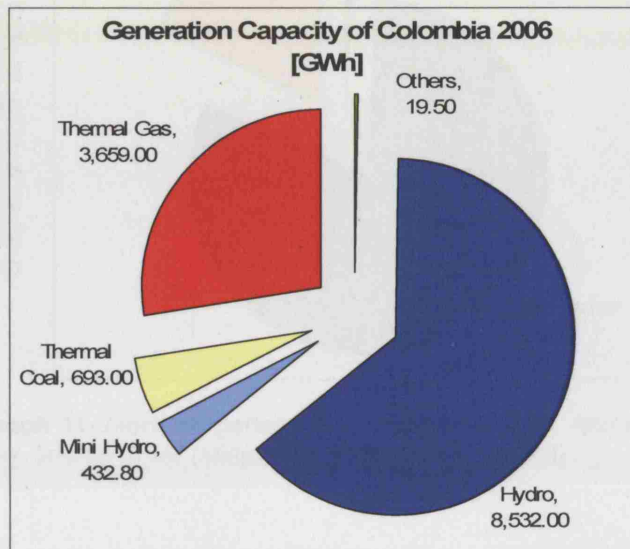
<sup>7</sup> "Meeting the Energy Needs of the Urban Poor: the Case of Electrification" Empresas Públicas de Medellín E.S.P. The experience of Empresas Publicas de Medellin (Colombia) in the supply of electricity to the urban poor Gabriel Jaime Betancourt.

## 1.2. Supply

### 1.2.1. Present Situation

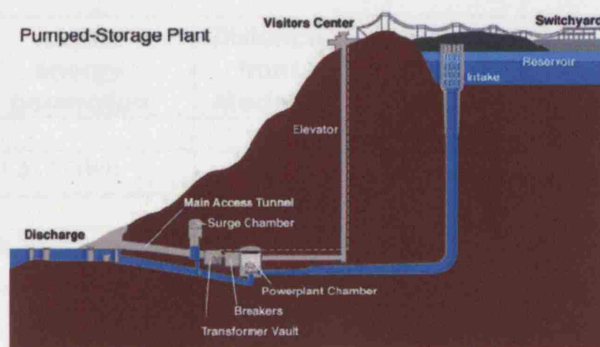
#### a. Colombia

The total amount of electricity generated during 2004 was 13,336.30 MW<sup>8</sup>. Of this, 66.53% was produced by hydroelectric schemes, 63.28% of which were on a large scale and 3.25% of which were of a small scale (not connected with the National Interconnected System)<sup>9</sup>. The percentage of electricity generated by thermoelectric schemes was 32.64%, of which burning natural gas and 5.20% by burning coal generated 27.44%. The least significant proportion of electricity (0.15%) was generated by other sources (mainly wind turbines and biomass).



Graph 09. Colombia generation capacity in 2006. Annual MW. Source UPME (Miner and Energy Planning Unit)

Hydro (Colombia's main source of electricity) refers to "the potential and kinetic energy of water being converted into electrical energy in hydroelectric plants".<sup>10</sup> The water accumulates in the reservoirs created by the dams. Regulated quantities of water are then allowed through the dam and then fall down to the gyratory elements, which convert the water's potential energy into mechanical energy. Hydroelectricity is so widespread in Colombia due to its very high precipitation rates and steep topography.



Graph 10. How a dam works? Hydro scheme diagram Source: [http://www.doc.ic.ac.uk/~mpj01/ise2grp/energystorage\\_report/node6.html](http://www.doc.ic.ac.uk/~mpj01/ise2grp/energystorage_report/node6.html)

<sup>8</sup> UPME Miner and Energy Planning Unit (Unidad de Planeación Minero Energética). Mineral Ministry. Expansion Program of generation and transmission of Energy 2005 – 2019 [www.upme.gov.co](http://www.upme.gov.co). 2005

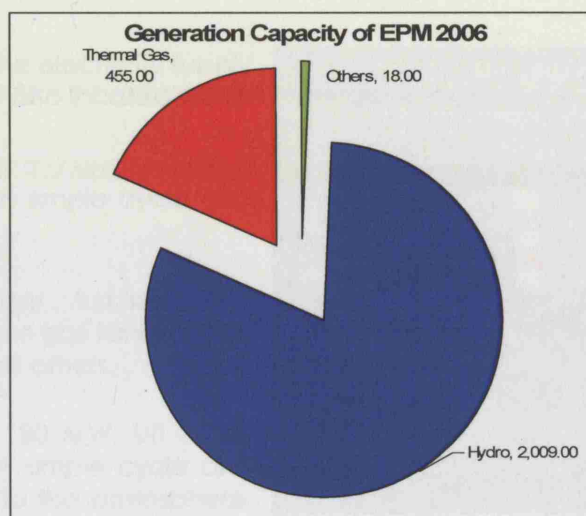
<sup>9</sup> SIN: National Interconnected System (Sistema de Interconexión Nacional). It is referred to the National Grid.

<sup>10</sup> EIA: International Energy Agency. STATISTICS Renewables Information. 2003



## b. Medellín

The electric supply for Medellín city comes from EPM<sup>11</sup> (Empresas Publicas de Medellín), which has a gross effective capacity of 2,482 MW (at 31-12-2005). Its generation represents 19% of the energy capacity of the whole country. This company owns 14 power stations, 12 of which are hydroelectric (80.94%), one of which is thermoelectric (18.33%) and one of which is a Wind Park (0.73%). All of them are connected to the National Grid and contribute to the National Supply. They are described as follows:



**Graph 11.** Medellín generation capacity in 2006. Annual MW. Source UPME (Miner and Energy Planning Unit)

**Hydroelectric dams:**

They represent 80.94% of the electric supply of EPM, with a gross generation of 2009 MW. All the Hydroelectric power stations are located within the region of Antioquia whose capital is Medellín and are described as follows:

	power station	Capacity	Annual energy generation	Distance from Medellín	Storage capacity and Extra Info
1.	DOLORES MINI				
2.	GUADALUPE III:	270 MW	1.617 GWh.		
3.	LA HERRADURA	19,8 MW.		142 Km	
4.	GUATEPE	560 MW.	2.730 GWh	100 km	1.070,21 millions m3
5.	NIQUIA	21.000 KW. 57.000 kW. Future		10 Km.	
6.	PAJARITO Mini	4.900 KW			Through out a "Francis" turbine.
7.	PLAYAS power	204 MW	1.380 GWh	160 Km	69,08 millions of m3
8.	PORCE	405 MW	1600 GWh	120 Km	
9.	TASAJERA	306 MW			
10.	TRONERAS	40 MW.	242 GWh.		
11.	LA VUELTA	11,8 MW.		160 Km.	

**Table 02.** Hydroelectric Power stations that supply Medellin. Source EPM (Empresas Publicas de Medellín)

<sup>11</sup> EPM (Empresas Públicas de Medellín). It is the company, which provides the public services for Medellín and it belongs completely to Medellín local authority.

### Thermoelectric Power Station

LA SIERRA Power Station represents 18.33% of the electricity supply of EPM, with a gross generation of 455 MW. It is also located within the region of Antioquia.

Its capacity is 460 MW. Of this, 294 MW are in simple cycle and 166 MW are in combined cycle.

The generators are running with two gas turbines. The infrastructure has an energy substation, storages gas tanks, water treatment plant and the interchanges, amongst others.

An extra vapour turbine has a capacity of 180 MW. UIT is the system that can achieve 35% of efficiency in simple cycle and 55% in combined cycle, thus reducing losses to the atmosphere, to just 10%.



**Pic 01.** Thermoelectric. La Sierra Power Station. Source: <http://www.eppm.com>

### Wind Park



**Pic 02.** Jepirachi Wind Park. Source: <http://www.eppm.com>

The "Jepirachi" is the first experimental Wind Park in Colombia, which started working in 2004. It is located far from Medellín (some 1,000 Km), in the north east of Colombia (La Guajira region). It represents almost the entirety of wind energy generated in the country, producing 18 MW that are connected to the National Grid.



### 1.3. Prospective

#### 1.3.1. An apparently easy solution

The above shows that the dynamic of the country is facing a higher demand for energy that in 14 years would represent a 75% increase. Therefore, the supply will have to increase accordingly. In principle, the hydroelectric production could be increased by taking advantage of the geography of the country that has plenty of rivers located in mountain areas. Furthermore, the gas and coal reserves in Colombia are substantial (3995 GPC)<sup>12</sup>

However, this could represent only apparently the best solution because of the following aspects that are taken into consideration:

#### a. Problems associated to Hydro:

##### Excessive dependency

As revealed before, the country and in particular Medellín mostly depend on the electricity generated by hydroelectric schemes. The hydroelectric schemes depend directly on climate fluctuations. During the years 1991 and 1992, this dependency was clearly seen because a deficit in the rainfall generated a rationing scheme for electricity that lasted 13 consecutive months. It caused significant losses and an increase in the price of electricity. That explains why the price of electricity depends directly on the precipitation regime.

Over the last years, after this rationing scheme, the electricity generators companies have monitored closely climatic conditions in order to be prepared for future drought events. Nevertheless, it doesn't secure that in the future the climate conditions became adverse, thus affecting the hydroelectricity production.

##### Security and centralization risks

Colombia, due to its internal guerrilla conflict, is a country subject to a very high risk, associated to the fact that the energy generation is concentrated in dams (points), which represent an easy target for terrorist group.

##### Habitat destruction

One of the biggest disadvantages related with large scale hydroelectric schemes is the fact that it has to flood a very large area upstream. This causes problems in the surrounding aquatic ecosystems, because the flora and the fauna that used to live in the river will be affected. This is supported by some studies that proved that the dams located near the North American coasts have reduced salmon populations because it prevents the access to spawning grounds in the reservoir.

Moreover, in many cases this requires that towns have to be evacuated. With the consequent social problems, such as those created in the 80's in Colombia with the Tomine dam, when Guatavita's town was flooded and the inhabitants had to move to another new town. Many of the people didn't like the new town and in no way could return to their former houses.

##### Costs of new infrastructure

The cost of a new dam is huge and requires the investment of the whole nation. It makes that the nation, in this case a developing country, has to rely on loans from international

<sup>12</sup> "Reservas de Gas Probadas Comercialmente". Proven Commercial Gas Reserves



banks, thus increasing its external debt. For example, the biggest hydroelectric constructed in Colombia "El Guavio" cost around \$2,500 millions in 1994.

#### b. Problems associated to Thermoelectric: CO2 Emissions (Climate Change)

The effects of climate change do not only come in the form of an increase in air temperature, but also in an "increase in global mean rates of precipitation and evaporation, rising sea level, and changes in the biosphere, among others."<sup>13</sup> In Colombia, besides these effects, climate change would contribute to the following risks: 50% of the hydrological system of the country would be vulnerable to change. The 22% of the land could undergo desertification. In addition, 95% of the snow covers and 75% of the "Paramos" could disappear.

#### 1.3.2. Political Responses, commitment and regulations

The government is aware of the environmental problems associated with energy generation and the Parliament ratified the Rio Convention of Climate Change<sup>14</sup> and Kyoto Protocol in 1995 in 2000 respectively. Furthermore, through Act 697 of 2001 the state committed itself to foster the rational and efficient use of energy and promotes the utilization of alternative energy sources, naming the following five: solar, wind, geothermal, biomass and small scale hydroelectric. This commitment was implemented by Decree 3683 of 2003.

One of the objectives of the energy expansion plan of the country is to evaluate the potential use of alternative ways of renewable energy to integrate them in the Colombian Interconnected System (SIN).

<sup>13</sup> [http://www.agu.org/eos\\_elec/99148e.html](http://www.agu.org/eos_elec/99148e.html)

<sup>14</sup> During the 80's, the increase of the greenhouse effect gases and the problems they have been caused to the environment were evidenced. As a result, global conventions were made in order to find alternatives which reduce the emissions of these gases. Consequently, many countries in particular the developed countries establish and sign commitments such as World political agenda with the earth summit in Rio in 1992, UN framework Convention on climate change and the Kyoto protocol in 1997. In particular, under the Kyoto protocol, "the European Union has committed itself to reducing the emission of greenhouse gases by 8% in 2012 compared to the level in 1990." In order to achieve this the energy generation has got a main relevance and the renewable technologies has been taken into account

## 2. POSSIBLE SOLUTIONS

In light of the previous analysis, the type of solution proposed will be conditioned in order to address the specific needs for the Country, Medellín and El Valle, and meet the required energy demand while the quality of life is not affected. However, the proposed solution will consider the quality of life of the population and the environment. The proposed solution will consider the quality of life of the population and the environment.

### 2.1. Renewable Energy Definition

According to the International Energy Agency (IEA), renewable energy is "energy that is derived from natural sources that are replenished at a faster rate than they are consumed. Renewable energy sources include wind, solar, hydro, geothermal, and biomass. Renewable energy is a key component of a sustainable energy system." (IEA, 2019)

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## 2. POSSIBLE SOLUTIONS



Figure 2.1: World energy sources. The percentage of world energy generated by different sources.

### 2.2. Types of renewable energy sources

#### 2.2.1. Wind energy

The use of wind to generate energy dates back to the first millennium BC, when windmills were used to pump water and grind grain. In the 19th century, windmills were used to generate electricity. Wind energy is a renewable source of energy that is clean and sustainable. Wind energy is a key component of a sustainable energy system.

<sup>1</sup> International Energy Agency (IEA) (2019)

<sup>2</sup> International Energy Agency (IEA) (2019)

<sup>3</sup> International Energy Agency (IEA) (2019)

<sup>4</sup> International Energy Agency (IEA) (2019)

<sup>5</sup> International Energy Agency (IEA) (2019)

## 2. POSSIBLE SOLUTIONS

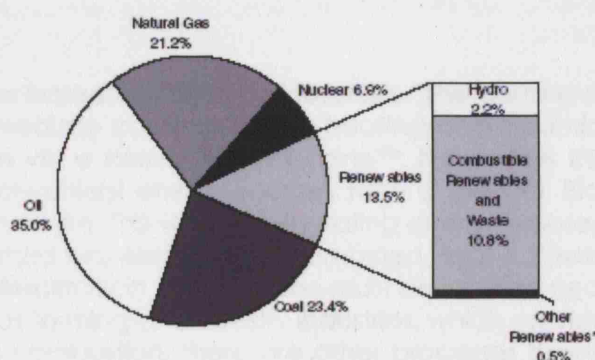
In light of the above, alternative ways of generating electricity will be considered, in order to evaluate if they are suitable for the Colombian climate and if they can meet the required energy demands. Since the nuclear option cannot be considered, because the Parliament ratified the "Total Prohibition of Nuclear Test" Treaty (Act 660 of 2001), only renewable technologies are left as a possibility.

### 2.1. Renewable Energy definition:

According to EAI, renewable energy is "energy that is derived from natural processes that are replenished constantly. In its various forms, it derives directly or indirectly from the sun, or from heat generated deep within the earth. Included in the definition is energy generated from solar, wind, biomass, geothermal, hydropower and ocean resources, biofuels and hydrogen derived from renewable resources."<sup>15</sup>

According to this definition, if hydroelectric power is included in the category of renewable energy technologies, the percentage of renewable technologies within the total primary energy supply of the world is 13.5% (1352MToe)<sup>16</sup>. However, the contribution of solar, wind and tidal energy is still negligible, as it represents just 0.1% of the total primary energy supply. Nevertheless, these technologies have experienced a substantial annual growth rate of 19.1%, compared to the other renewables since 1990.

**Figure 1: 2001 Fuel Shares In World Total Primary Energy Supply**



**Graph 12. World Energy Supply, showing the percentage of renewables. Source EIA.**

### 2.2. Types of renewable technologies:

#### 2.2.1. Wind Energy:

The use of wind to generate energy dates back to the time when windmills were built for pumping water and milling grains. Towards the end of the 19th century, the development of an automatically operating wind machine<sup>17</sup> was the first step to be taken to transform mechanical energy into electrical energy. Then, with new developments in the wind power technology, it gradually became a significant option to burning fossil fuels for large-scale electricity generation. Wind energy is exploited using wind turbines that are driven by the wind. The generator transforms the kinetic energy of the turbines into electrical energy.

<sup>15</sup> EIA: International Energy Agency. STATISTICS Renewables Information. 2003 Introduction

<sup>16</sup> EIA: International Energy Agency. STATISTICS Renewables Information. 2003

<sup>17</sup> The first wind machine was developed by Charles F. Brush in the USA, 1888. It an automatically operating wind machine performing a rated power of 12 kW



### 2.2.2. Solar Energy:

Harnessing the sun's energy is a clean, simple and natural way of generating energy. It can be transformed into electrical or heat energy that can also be used to produce steam that can generate electricity. The first technology that transformed the sun's energy directly into electricity was patented by Bell Labs in 1955 and was based on silicon. Since 1973 the extensive development of this technology meant that the cost was reduced by 20 times. The most common uses are: water and air heating, electricity generation for different purposes, cooling systems, communication systems and transport, among others.

Since 1993, the solar collectors have experienced an annual growth rate of 14.8%.

### 2.2.3. Tidal Energy:

This works by the principle of converting kinetic and potential energy into electrical energy. This is achieved by capturing the energy contained in water masses moved by the tides. One of the methods used to obtain the energy generated by tides is to build a barrage that traps the water in an artificial lagoon. Within the barrage are located the turbines which are moved by the water flowing through them to the side that has the lower water level, thus producing electricity. The efficiency of tidal power generation in oceans depends directly of the amplitude of the tidal swell that might be 10m.

### 2.2.4. Bio Energy:

Biomass is the oldest renewable energy source based on direct combustion. "The burning of biomass produces heat and/or steam for immediate cooking, space heating and industrial processes or for indirect electricity generation via a steam driven turbine"<sup>18</sup>. Nowadays the fossil fuels have been substituted by more convenient energy sources such a bio-fuel. Bio-energy varies depending on its source type and form. This way of generating energy is based on heat production that can then be transformed into electricity in Combined Heat & Power plants (CHP). In order to be able to generate electricity in this way, one must be located near to where a biomass source is abundant, such as farming and forestry industries, which provide the various feedstocks. Apart from traditional combustion, there are other processes based on the same principal and they are as follows: Pyrolysis, Gasification and Anaerobic digestion.

### 2.2.5. Geothermal

It is the energy that can be obtained from the Earth, which can be "tapped into to produce electricity in power plants"<sup>19</sup>. It also produces hot water that is used for industry, agriculture, bathing and cleansing. Nowadays, its potential as an energy source is not yet been fully tested. It hasn't experienced a significant growth from 1991 to 2001, just 1.2%<sup>20</sup>. This source of energy can be developed in two ways: using wells and power plants that use hot water and steam and ground source heat pumps, in which the earth acts as storage, because "when the sun shines on the ground its heat energy is absorbed"<sup>21</sup>.

### 2.2.6. Comments on renewable energy:

None of the above would be able to satisfy the whole demand of an industrialized area. However, in the short term, they have been proven to alleviate the supply needs and in the long term, they might constitute an energy alternative that is environmentally friendly and helps to reduce reliance on the world's dwindling fuel reserves.

<sup>18</sup> EIA: International Energy Agency. RENEWABLES FOR POWER GENERATION. 2005

<sup>19</sup> National Energy foundation. <http://www.nef.org.uk>

<sup>20</sup> International Energy Agency. STATISTICS Renewables Information. 2003

<sup>21</sup> National Energy foundation. <http://www.nef.org.uk>

### 2.3. Why Solar Energy?

Any of the above renewable energy technologies reviewed, solar energy is worth investigating further. However, as this dissertation is focused on technologies that have already been tested in Colombia, rather than on theoretical approaches, only solar and wind energy are valid.

Between these two, Solar Energy has been preferred because this resource is available in most of the country, including urban areas. It is also a technology with relatively easy installation in individual buildings at a relatively low cost, whereas wind energy is available in fewer areas, and its installation costs are higher.

### 2.4. Solar Technologies: Passive Solar:

The passive solar energy is the one method whereby the design and the materials of the building can be used to reduce the load of cooling and heating load for buildings.

One of the most important components in passive solar energy generation is the use of glazed areas, which are used to give day lighting and can also be used to achieve heating or to reduce heating requirement for the building. After all they help to reduce the energy consumption of the building, for example when using day light instead of artificial one.

In a building, external heat gains are directly proportional to the glazing on the external surface, as well as the sun-protection concept. "The best external sun-protection reduces this irradiation by 80%."<sup>22</sup>

### 2.5. Solar Technologies: Passive : Active Solar:

Active solar energy is referred to the use of solar radiation to produce electricity, heating or cooling through the use of technological systems. It is subdivided into two main sectors, solar thermal devices, which use the sun's heat, and photovoltaic cells and modules, which use the photons present in the sunlight. The solar industry grew significantly as a consequence of the oil embargo in the 70s.

#### 2.5.1. Advantages:

Active solar technologies are a very good solution because they can be presented as decentralized energy generation, which "serves to reduce overall generating cost at any given level of risk, even where their stand-alone costs are higher"<sup>23</sup>. As a consequence of this decentralization, the planners and architects, who were accustomed to designing for centralized electricity, which is separate from the urban centres, have a new challenge. This is because when a new technology is available, "current architecture would be re-invented"<sup>24</sup>.

<sup>22</sup> EICKER, U. 2003. *Solar Technologies for Buildings*. West Sussex: Wiley and Sons Ltd. Page 8

<sup>23</sup> Princeton Environmental Institute, Princeton University. Energy Policy 31 (2003) Small is profitable

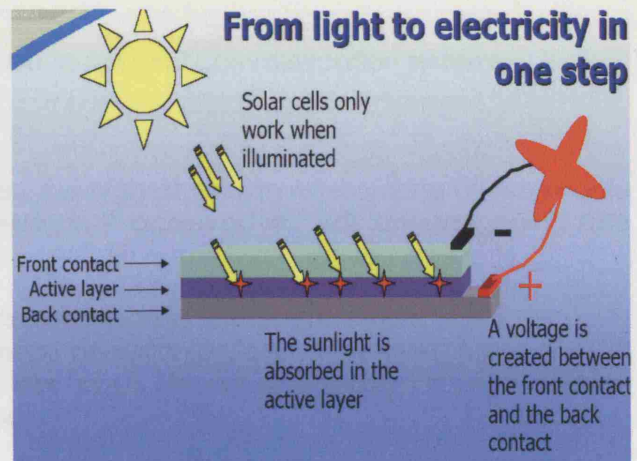
<sup>24</sup> Princeton Environmental Institute, Princeton University. Energy Policy 31 (2003) Small is profitable



### 2.5.2. Photovoltaic

#### a. Concept

The photovoltaic system converts light energy into electrical energy directly. This is because the panels' main component is silicon, which becomes polarised when it is combined with other specific materials and exposed to sunlight. The sunlight is composed of photons, which are extremely small packets of radiant energy. When photons strike a photovoltaic cell, the photon transfers its energy to an electron and it produces an electric reaction. In this reaction, the photons that come from the light act on the electrons that starts moving through the silica (semiconductor device), producing an electrical flow.



**Graph 13.** Photovoltaic Diagram. Source: European Commission. Procis Project.

The efficiency of the system is about 10% to 15%<sup>25</sup>. This means that from every square metre of PV, it is possible to obtain between 100 to 150W, which can be used to run a standard television. For example, a crystal silicon solar module can produce "5000 to 6000 KWh/year in Northern Europe and 7000-8000 kWh/year in sunniest parts of Europe (12.5 % efficiency)."<sup>26</sup>

The system could store surplus energy in batteries, to be used when sunlight is at low levels. However, this would make the system more expensive.

#### b. Types

The two main types of photovoltaic panels are: cell technology and module/array technology.

The *cell technologies* include "single crystal Czochralski silicon, semi crystalline silicon, polycrystalline thin-film, and amorphous silicon".<sup>27</sup> The most popular are the amorphous silicon cells, which are predominantly composed of a thin silicon film, called amorphous. It is arranged in layers of a non-crystalline silicon material, which is deposited on a piece of glass.

The *module/array technologies* include "flat-plate and concentrator modules"<sup>28</sup>. The flat plate consists of cells put together into a flat panel, covered by a transparent cover. It protects the cell from water and dust, but allows the sunlight to pass through. The concentrator modules consist of different lenses that focus the incident sunlight onto the photovoltaic cells.

<sup>25</sup> Greenpeace. Mexico. The renewable energies in Mexico and the world.

<sup>26</sup> European Commission, Community Research. Procis Project: EC RTD Renewables Energies Press Briefing. Uppsala 16 November 2004.

<sup>27</sup> US Energy Information Administration. Renewable Energy Annual 1998. Chapter 6: Solar Industry Profile

<sup>28</sup> US Energy Information Administration. Renewable Energy Annual 1998. Chapter 6: Solar Industry Profile

### c. Uses

The greatest proportion of photovoltaic cells and modules has been used for electricity generation. They are also used in the communications sector and for transportation at a lower scale.

In Colombia, the system is most commonly used to run rural communication systems.

### d. Advantages

In the world, the system that has experienced the highest growth rate among all renewable energy products is the solar photovoltaic system. It achieved a "32% annual growth rate between 1990 and 2001".<sup>29</sup>

The benefits of generating electricity using photovoltaic panels are as follows:

A photovoltaic system provides, in the case of air conditioning, electricity when it is needed. It has their peak output when air conditioning is required. This pattern makes PV apt to reduce the peak loads on the general electricity supply.

When photovoltaic systems are in use, greenhouse-gases are not emitted. As a result, the risks posed by global warming are alleviated to a certain extent and air-quality is improved. In addition, if energy generation takes place directly where the energy is utilised, the air pollution caused by transmission and distribution is reduced.

### e. Disadvantages

During periods of significant amounts of sunlight (4kWp), the system can produce more electricity than the household is consuming. If the system does not possess batteries or is not connected to the grid, the surplus electricity is lost. However, the batteries to store the electricity are very expensive and make the system less feasible. The other possibility is to connect the system to the national grid, which is inconvenient due to the lack of mechanisms to connect the PV systems to the grid. In addition, the owners of PV systems that have produced surplus energy and that have been connected to the grid system would have to pay for the electricity that the mechanism they paid for produced in the first place.

The photovoltaic output is very difficult to capture because it is usually not connected to the grid.

Its production takes a lot of energy, approximately "150 kWh to make 1 m<sup>2</sup> of thin film solar module".<sup>30</sup>

### f. Costs

Nowadays, photovoltaic technology does not compete with conventional electric generation. Nevertheless, its prices are likely to take fall considerably as it is being used more and more in residential premises. The increase in the number of residential premises and technological advances has also contributed to this. The unitary cost per Watt produced has fallen by 20 times since 1973<sup>31</sup>.

However, solar technologies cannot be evaluated with just costs in mind, environmental benefits have to be assessed too; for instance considering the reduction in greenhouse gas emissions and expenditure of fossil fuels. The air pollutant mitigation value of PV is "about

<sup>29</sup> International Energy Agency. STATISTICS Renewables Information. 2003

<sup>30</sup> European Commission, Community Research. Procis Project: EC RTD Renewables Energies Press Briefing. Uppsala 16 November 2004

<sup>31</sup> Greenpeace. Mexico. The renewable energies in Mexico and the world.



seven times the direct generation cost for coal electricity"<sup>32</sup>. For example, in California the mitigation value is \$0.018/ kWh produced.

### 2.5.3. Solar Thermal Panels

#### a. Concept

Generally, the solar thermal systems collect the thermal energy from solar radiation and use it directly in thermal applications, such as heating swimming pools, domestic hot water systems, heating spaces, heat transformation or thermo-mechanical processes. Nowadays the developments of the solar collectors are still taking place. The aim is to improve the efficiency of the panels and this can be achieved by using different methods such as "using selective coatings of absorbers, optimizing the heat transfer from the absorber to tubes through improved welding or soldering technologies, reducing glazing reflection losses through antireflective layers, optimizing vacuum collector geometry and introducing low level concentrations of the irradiance (CPC collectors)"<sup>33</sup>. Currently, the solar collectors can be classified by temperature or type. In the temperature classification there are three main groups: "low-temperature, medium-temperature, and high temperature"<sup>34</sup>. In the type classification there are two main groups: *Flat* and *Parabolic*.

#### b. Types

##### By Temperature:

The low- temperature solar collectors work with metallic or non metallic absorbers that can heat up to 45 °C. They are commonly used for heating water systems, especially in swimming pools. Usually, for swimming pools, the heat that comes from the solar radiation is transferred directly from a black absorbing material (black plastic or rubber) to the water that is circulating through the tubes.

The medium-temperature group collectors can heat the air or the liquid to between 60°C and 80°C. The glazed flat-plate and evacuated tube collectors are located in this group. They are used for hot water requirements and for heating spaces.

High temperature collectors operate at temperatures higher than 85°C. They concentrate in smaller areas large amounts of solar radiation to reach very high temperatures. The parabolic trough is classified in this category.

##### By Type:

The *flat solar collectors* are also called heat pipe solar collectors or vacuum tube collectors. They are flat boxes that work by applying the greenhouse effect principle. It is composed mainly of a transparent cover, an insulated container and the fine tubes where fluid is circulated. The incident solar radiation falls on the collector and is transmitted through the transparent surface. The solar energy is then trapped inside and the heat is transferred to the fine tubes. These tubes are usually made of copper and the container is insulated and painted black to absorb the solar radiation and avoid heat loss. They can heat up the fluids up to 200°C in the evacuated tubes system, though usually the temperatures only reach 75°C.

This simple technology is experiencing a high growth rate throughout the world, especially in Europe, where since 1993 the annual growth rate has been 14.8%.

<sup>32</sup> Accelerating Pv expansion.

<sup>33</sup> Solar Technologies in Buildings.....

<sup>34</sup> EIA (Energy Information Administration). Renewable Energy annual 1996. Chapter 6. Solar Industry. Page 50. Washington: US



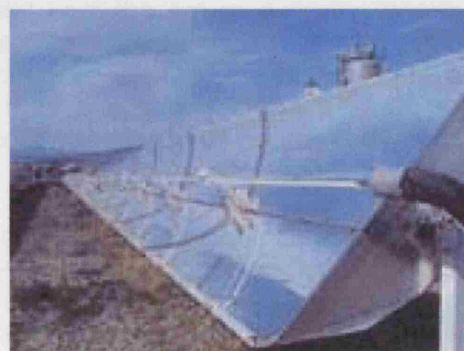


**Pic. 03.** Flat collector.



**Pic. 04.** Evacuated tube collectors

This type of collector works for higher temperatures and is very useful for applications that require temperature levels of 150°C or more, like some solar cooling systems. This collector is more efficient because it can reach temperatures of between 100°C and 200°C.



**Pic. 05 & 06.** Parabolic concentrator collectors.

A *parabolic collector* is defined as a system that "operates by tracking the sun and reflecting the solar energy focused of the dish". The sunlight is focused on a receiver, which is a tube that carries a heat-absorbing fluid, usually oil or liquid sodium. It then works as a conventional steam cycle technology that produces electricity. Within it, "the fluid is circulated through a boiler, where its heat is used to boil water. The steam is then routed to a turbine to generate electricity".<sup>35</sup> If many parabolic panels are placed, they can operate as power plants, as their size ranges from 5 to 40KW.

<sup>35</sup> EIA (Energy Information Administration). *Renewable Energy annual 1996*. Chapter 6. Solar Industry. Page 50. Washington: US

### 2.5.4. Solar Cooling

#### a. Concept

In order to define the solar cooling system it is necessary to explain what cooling and air conditioning means. What is meant by air conditioning is the control of internal conditions such as temperature, humidity and ventilation in order to provide comfortable conditions for the occupants.

However, the major problem with the use of air conditioning systems in buildings is that their units are mostly run on electricity (peak electricity), especially the compression cooling units. This puts a strain on the environment because, to generate electricity, fossil fuels must be utilized, increasing carbon dioxide emissions.

Energy consumption for air conditioning units is rising rapidly. "This growth is due to increasing needs for thermal comfort, higher working and living standards in combination with increased internal loads from office equipment"<sup>36</sup>.

The solar cooling systems are directly dependant on the solar radiation available at a specific site and on the capacity of the collector to capture the solar radiation.

The principle of solar cooling is to use the heat from the sun as a driving energy for cooling processes. The advantage of this in comparison to a conventional cooling machine is that it reduces the high electricity peaks and as a consequence, the high-energy consumption. Because they are driven by solar energy, they are called clean systems. They are very efficient in the way that they can produce cooling when solar energy is available and when cooling is most needed.

Solar cooling can be used in two different ways. The first one helps the conventional systems to reduce the energy consumption. This is done by introducing the heat coming from the sun into the major driving energy source. This kind of system is called Solar Assisted system and "The system design is accounted as the energy fraction provided by the solar system for cooling".<sup>37</sup> The second one is the Solar Autonomous, which uses the solar energy as the only energy source.

#### b. Collectors in the system

The functions of the solar collector are to convert the solar radiation into thermal energy to drive the cooling system. It is the first step and the main component of the system. Within it, the central component is the *absorber*, within which "the absorbed solar radiation is transformed into heat. Part of this heat is transferred to the heat transfer fluid and another part is lost to the environment".<sup>38</sup>

The collector efficiency is the relationship between the useful heat output and the global incident radiation on the collector, which varies depending on the fluid temperature. As a consequence, the higher the solar radiation is, the higher the efficiency of the system. The evacuated tube collectors are the most efficient solar collectors for the single effect absorption cooling system. They consist of different single tubes that are joined to a main tube. The fluid moves through them and they heat up. All the tubes are vacuumed to reduce heat losses.

<sup>36</sup> SACE, "Solar air conditioning in Europe- Accompanying measures", European commission, evaluation report NNE5/2001/25, Aug 2003

<sup>37</sup> Hernandez, Raquel. SOLAR ABSORPTION COOLING. 2004. Page 26

<sup>38</sup> Henning, H. "SOLAR ASSISTED AIR CONDITIONING IN BUILDINGS". International Energy Agency, Springer Wien New York (2004)



### c. Types of Solar Cooling

The technology is divided in two main groups, close cycle and open cycle. The close cycle uses different fluids as refrigerants, such as ammonia. It takes its name because its refrigerants are not in contact with the atmosphere. On the contrary, the open cycle always uses water as a refrigerant whilst it is in contact with the atmosphere. Both cycles can be powered by active solar components. This is the reason why solar collectors are very important to the system. Two systems that are commercially available and that are powered by solar thermal energy are as follows: absorption refrigeration (close cycle) and desiccant cooling (open cycle).

#### C.1. Close cycle

Close cycle machines are characterized because they produce chilled water. This water can be used in different kinds of air conditioning machines, such as handling units for central treatment of fresh air, fan-coil systems, chilled ceilings, silent cooling systems, etc...

One of the disadvantages of the close cycle units is that they use less environmentally friendly refrigerants such as distilled water (Lithium bromide/water cycle) and ammonia (Water/ammonia cycle).

## ABSORPTION COOLING

### I. The concept of Absorption cooling

"Absorption cooling is a process by which the refrigeration effect is produced through the use of two fluids and some quantity of heat input. This heat input can come from the sun, rather than electricity as in the vapour compression cycle"<sup>39</sup>, which uses a mechanical compressor to create the difference of pressure necessary to run the refrigerant. The absorption refrigeration cycles work similarly to vapour compression cycles, which use the evaporation of refrigerants in relatively low pressures to remove the heat. "The low pressure is created by the affinity of a liquid (absorbent solution) to draw the refrigerant gas into a solution"<sup>40</sup> at higher pressure and reject the heat by condensation of the refrigerant. It uses direct heat to vaporise the refrigerant, which is usually water/ammonia or water/lithium bromide.

The main difference between both systems is that absorption cooling requires much less electrical power. This is because instead of a compressor, it uses an evaporator, which operates with a chemical absorber and a pump that provides pressure to the system.

There is significant potential for electrical energy savings using the absorption cooling system because the temperature requirements for this cycle are in the low-to-moderate temperature range.<sup>41</sup> The heat input necessary to run the system is basically hot water that can be obtained by different sources such as gas or solar collectors. If solar collectors are used, the system saves energy, which reduces the running costs and at the same time decreases the CO<sub>2</sub> emissions considerably. When solar collectors are used, the system is called solar absorption cooling. It is configured to run with water heated between 80°C and 120°C; these temperatures are lower than the gas absorption cooling systems. In addition, the coefficient of performance of the system (COP) can be, theoretically, about 0.7 for single-effect.<sup>42</sup>

<sup>39</sup> Kim, D.S. SOLAR ABSORPTION COOLING, Report K-332. Delft University of Technology. 2003.

<sup>40</sup> Source: The Government's Energy Efficiency Best Practice Programme, *General Information Report 85: New Ways of Cooling – Information for building designers*, Crown Copyright, September 2001; page 18

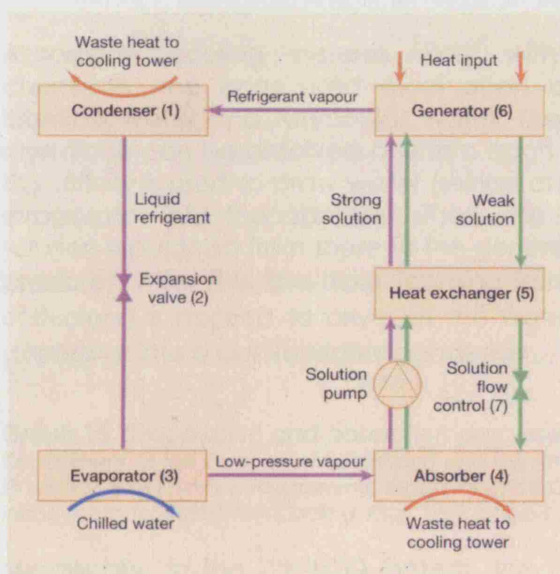
<sup>41</sup> Rafferty, K. "ABSORPTION REFRIGERATION", Geo Heat Center, Oregon.

<sup>42</sup> Hernández, Raquel. SOLAR ABSORPTION COOLING. 2004.

## II. Types of absorption cooling: LiBr/H<sub>2</sub>O and NH<sub>3</sub>/H<sub>2</sub>O

There are two types of absorption cooling systems; the Lithium Bromide/Water (LiBr/H<sub>2</sub>O) system and Water/ ammonia (H<sub>2</sub>O/NH<sub>3</sub>). In the Lithium Bromide/Water (LiBr/H<sub>2</sub>O) system the distillate water is the refrigerant and lithium bromide is the absorbent. The cooling temperature of the system is about 6°C. On the contrary, in the water/ammonia system the refrigerant is the ammonia and the absorbent is the water. Its cooling temperature is below -30°C<sup>43</sup>. However, between both systems, the LiBr/H<sub>2</sub>O is preferable, as the "ammonia has a negative impact on global warming"<sup>44</sup>.

## III. Components of the absorption cooling systems



The system is divided into two main sides; the lower-pressure side and the higher-pressure side. The main components are the evaporator and the absorber for the first one and the generator and the condenser in the latter. The other components of the system are: (2) expansion valve, (5) heat exchanger and (7) solution flow control.

**Graph 14.** Absorption Cooling system. diagram.  
Source: The Government's Energy Efficiency Best Practice Programme, General Information Report 85: New Ways of Cooling September 2001; page 18

<sup>43</sup> Hernández, Raquel. SOLAR ABSORPTION COOLING.2004

<sup>44</sup> Kim, D.S. SOLAR ABSORPTION COOLING, Report K-332. Delft University of Technology. 2003

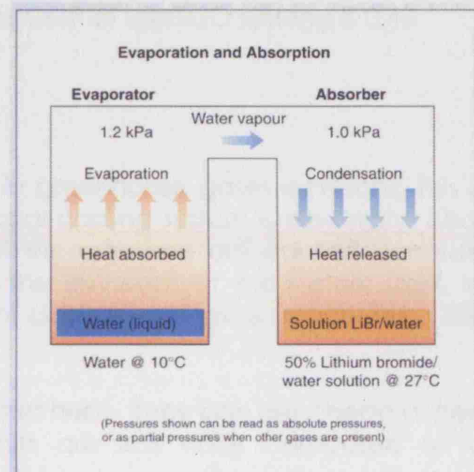


#### IV. Processes of absorption cooling systems

The following is based on the graph above, which shows a diagram of the process. The process begins when the strong solution (magenta line) is pumped into the generator. There, the heat input vaporizes the solution and the refrigerant is separated. Then, the refrigerant vapour (high pressure) passes to the condenser, where it is transformed into liquid refrigerant by condensation caused by chilled water from a cooling tower. The weak solution (green line) is returned from the generator to the absorber. On the way, it passes through a heat exchanger and a control device. They then preheat the strong solution and help to maintain the pressure difference respectively. In this process, the water that enters the generator at 29.4°C is cooled to 6.7°C, giving a COP of approximately 0.65 to 0.70<sup>45</sup>.

Absorption cooling systems work with pairs of chemicals; the ones used most often are Lithium Bromide/Water and Ammonia/ water. These pairs of chemicals can be dissolved one into each other, and this affinity is used to draw water (refrigerant) from the evaporator into the absorber. Then, the weakened solution is pumped from there to the generator (higher pressure). After this, the heat (coming from the solar collectors) is applied to drive off the water from the generator into a conventional condenser.

**Graph 15.** Evaporation and absorption processes Source: The Department of the Environment, Transport and the Region's Energy Efficiency Best Practice Programme, Good Practice Guide 256: An Introduction to Absorption Cooling. May 1999; page 4



Specifically, in the LiBr/H<sub>2</sub>O System, the heat is applied to this solution where the water (refrigerant) is evaporated out in a distillation process. Its vapour passes through the condenser and comes back to liquid a state. Then at this state it leaves the evaporator and flows through tubes where it is cooled down. The strong solution of LiBr (refrigerant) "tends to absorb the vapour from the evaporator section, completing the absorption process that gives the cycle its name"<sup>46</sup>.

#### V. Efficiency

One of the factors that show how efficient is the energy conversion of the system is the Coefficient of Performance (COP). The COP of a refrigeration machine is achieved by dividing the cooling effect produced (energy received at the evaporator) by the energy supplied to the machine. An idealised Carnot cycle is presented as:

$$COP_{carnot} = \frac{T_e}{T_c - T_e}$$

where  $T_e$  is the evaporating temperature in kelvin  
and  $T_c$  is the condensing temperature in Kelvin

However, this ideal formula is just for refrigeration machines, but also for Absorption cooling systems, where it is about 80%. Nevertheless, for the systems drive by the solar energy two more factors have to be analyzed:

- **Thermal COP:** It is referred to "the ratio between useful thermal effect and required energy input to the system." This 'useful thermal effect' is referred to the cooling capacity and the 'energy input' to the heating power delivered to the solar cooling systems from the solar collectors. The equation is shown above:

<sup>45</sup> ASHRAE: American Society of heating, refrigeration and Air conditioning Engineers. 1983 HANDBOOK OF FUNDAMENTAL. 1983.

<sup>46</sup> Hernandez, Raquel. SOLAR ABSORPTION COOLING.2004, page 23

$$COP = \frac{\dot{Q}_{cooling}}{\dot{Q}_{heating\_power}}$$

- Solar COP: The same equation of thermal cooling is applied and it is multiplied by the efficiency of the collector in design conditions.

$$COP_{solar} = COP_{thermal} * \eta_{collector}$$

Based on the SACE project, the average of thermal COP of LiBr/H<sub>2</sub>O systems is 0.66 and for NH<sub>3</sub>/H<sub>2</sub>O systems is 0.60. In addition, the average of solar COP of LiBr/H<sub>2</sub>O systems is 0.46

## VI. Advantages and Disadvantages

The biggest advantage of the system is the reduction in greenhouse gases emissions. This is due to the fact that the Total Energy Input in a traditional cooling system is electricity. Also, according to the International Energy Agency, 98% of the emissions are caused because they are running on electricity and just 2% is due to the emissions of the system itself. In addition, the energy consumption of an absorption cooling system is much less, 7%, compared to a vapour pressure system.

Other advantages are that the system recycles the wasted heat. They can use cheap or free (solar) thermal sources. In addition, the cooling units are less noisy compared to a conventional system.

The disadvantage is its low COP, because whilst for absorption cooling the COP is 0.7, for a conventional system (vapour compression) it is 3 or higher. Given that fact, the indoor conditions have a complete dependency on the solar radiation available to run the system.

## ADSORPTION COOLING SYSTEMS

The adsorption systems works with substances such as silica gel or zeolite, which adsorb the water, which acts as a refrigerant. This system is normally an exothermal process that rejects the energy out of the system. The heat of adsorption is removed by heat exchangers present in the system.

This systems has a low COP of 0.59 and it can apply lower driving temperatures 53-82°C<sup>47</sup>

<sup>47</sup> European Commission. Evaluation Report. SACE: Solar Air Conditioning in Europe. August 2003.



### C.2. Open Cycle

The open cycles are based on the combination of air dehumidification and evaporative cooling. Basically, the mechanism removes moisture from the environment and makes the air feel cooler, as it uses the cooling and dehumidification of the air as direct treatment.

The process is based on a desiccant substance that adsorbs the moisture present in the air through silica gel or lithium chloride. First of all, the air is cooled by an evaporative cooling or vapour compression cooler and then this dry air is distributed throughout the building. In this system, the heat is used to remove the moisture when the desiccant gets saturated. This system is very useful for solar cooling applications.

#### a. Types

This system is divided in two types, liquid desiccants and solid desiccants. The usual driving temperature for liquid desiccants is 67°C and the average thermal COP in the projects evaluated by SACE project was 0.74. On the other hand, the thermal COP of the solid desiccant system is 0.51.

### C.4. Heat Storage

To make the solar cooling system autonomous a storage tank for the hot water is required. This is due to the fact that sometimes, when the cooling is needed, the solar source is not available. With the use of this storage tank the net collector efficiency and the solar fraction cooling can increase.

The main advantage of the heat storage tank is that it stores the excess heat at the right temperature in order to use it when there is not sun available. As a consequence the operation times of the main system are extended.

In order to calculate the storage size for the system the following formula can be used.

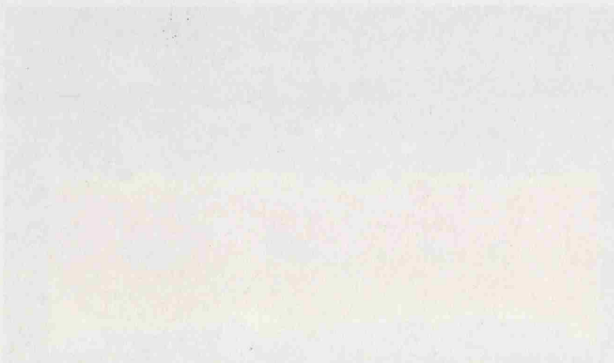
$$t_{\text{storage}} = \frac{\rho_{\text{chilled\_water}} V_{\text{storage}} c_p (T_{\text{chilled\_water\_in}} - T_{\text{chilled\_water\_out}})}{\dot{Q}_{\text{cooling}}} 3600$$

Where;

$t_{\text{storage}}$  is given in hours,  $\rho_{\text{chilled\_water}}$  is the density of the chilled water in kg/m<sup>3</sup>,  $V_{\text{storage}}$  the storage in m<sup>3</sup>,  $c_p$  the specific heat of the chilled water in kJ/kgK, and the cooling capacity  $\dot{Q}$  expressed in kW.<sup>48</sup>

<sup>48</sup> European Commission. Evaluation Report. SACE: Solar Air Conditioning in Europe. August 2003.

## 3. Case Study





### 3. Case Study

#### 3.1. Context

##### 3.1.1. Geographical and Climate Description:

Climate can be defined as the predominant atmospheric conditions in a place or region during a specific period of time. It is a very important factor because it influences human, social and economic activities. The climate can determine the potential of each region. For example, if a region is particularly windy, it will have greater potential for developing wind energy, another with great and constant solar exposure will be suitable for solar energy exploitation, etc.

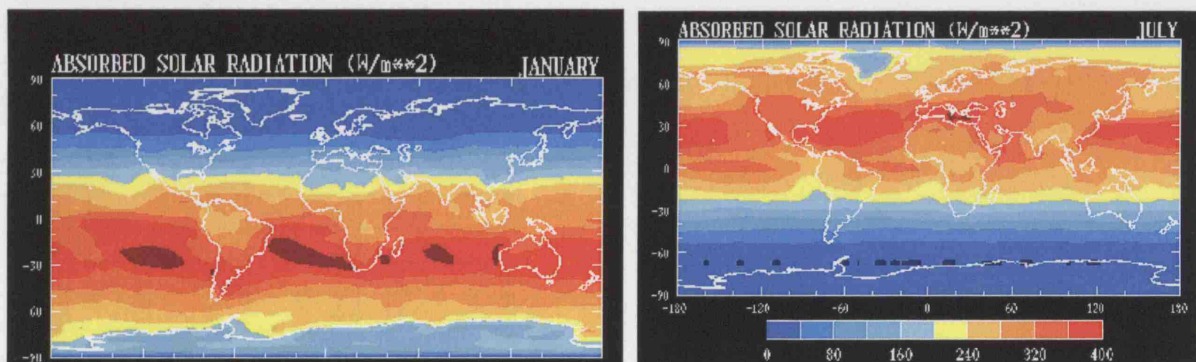
##### a. Latitude (Equatorial Climate)

Countries located between latitudes 10°N and 10°S are characterised by an equatorial climate. Due to the absence of seasons, the temperature and humidity are generally high and constant throughout the year. Also, the durations of daytime and nighttime are very similar (12 hours).

Medellín is a city located in northwest Colombia. Due to its equatorial location (latitude 12.5°N and 4.2°S), the country benefits from substantial quantities of solar radiation throughout the year.

##### b. Solar Radiation

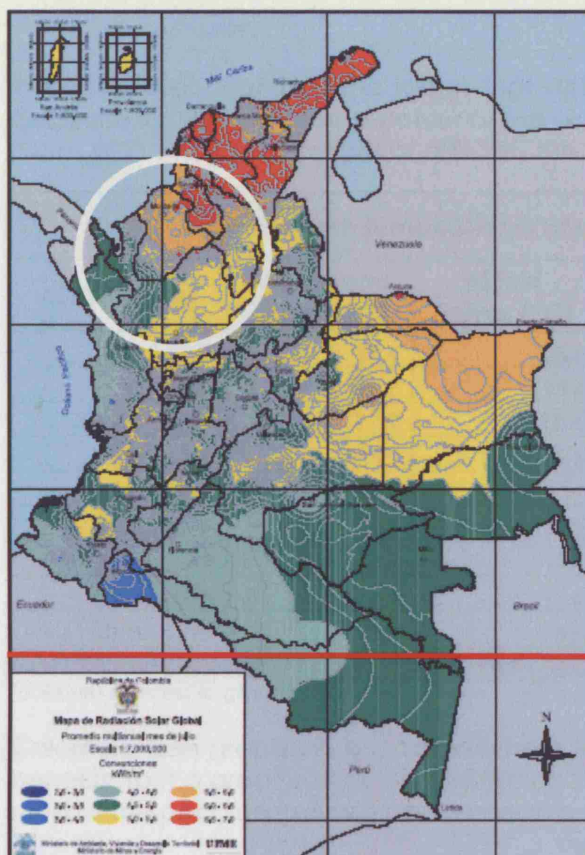
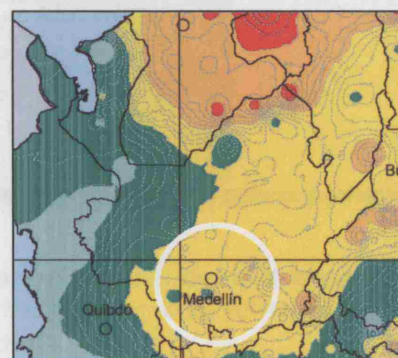
Solar radiation is a very important factor in this study. As shown by graph ....., the absorbed solar radiation for northern latitudes varies because of the seasons and is between 100 W/m<sup>2</sup> to 160 W/m<sup>2</sup> in January and 200 W/m<sup>2</sup> to 320 W/m<sup>2</sup> in July. In Colombia, solar radiation is nearly constant all year-round and it is between 250 W/m<sup>2</sup> and 320 W/m<sup>2</sup>. As a result, Colombia has a great potential for developing solar energy when compared to northern latitudes.



Graph 16: Global Absorbed radiation (W/m<sup>2</sup>)<sup>50</sup>

Taking into account the aim of this study, solar radiation requires a deeper analysis. In Colombia, as can be seen in the graph ....., the incident solar energy varies a lot, going from 2.5 kWh/m<sup>2</sup> to 6.5 kWh/m<sup>2</sup>.

<sup>50</sup> <http://eesc.columbia.edu/courses/ees/slides/climate/swrad.gif>

Graph17: Map showing Incident solar radiation ( $W/m^2$ ) in ColombiaGraph 18: Map showing Incident solar radiation ( $W/m^2$ ) in Medellín and Antioquia

Medellín, on average, has an incident solar radiation that ranges from 4.0 to 4.5  $kWh/m^2$ . Although it is rather constant, there are variations throughout the year, as detailed in the table below:

INCIDENT SOLAR RADIATION MEDELLÍN.	
MONTH	Incident SOLAR RADIATION Range (KW h/m2)
January	4.0 – 4.5
February	4.0 – 4.5
March	3.5 – 4.0
April	3.5 – 4.0
May	4.0 – 4.5
June	4.5 – 5.0
July	5.0 – 5.5
August	4.5 – 5.0
September	4.0 – 4.5
October	3.5 – 4.0
November	3.5 – 4.0
December	4.0 – 4.5
<b>Annual Average</b>	<b>4.0 – 4.5</b>

Table 03: Incident Solar radiation ( $W/m^2$ ) in Medellín.



## c. Altitude:

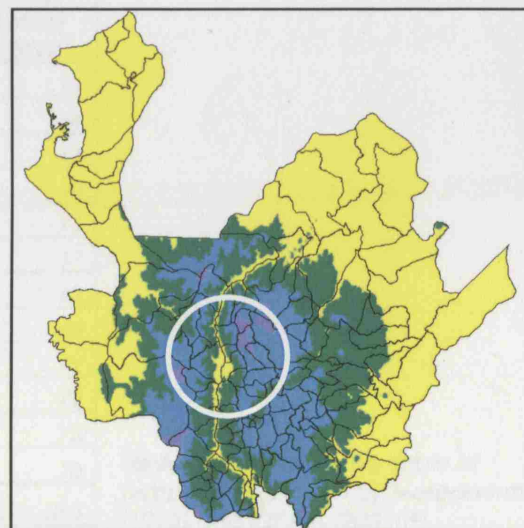
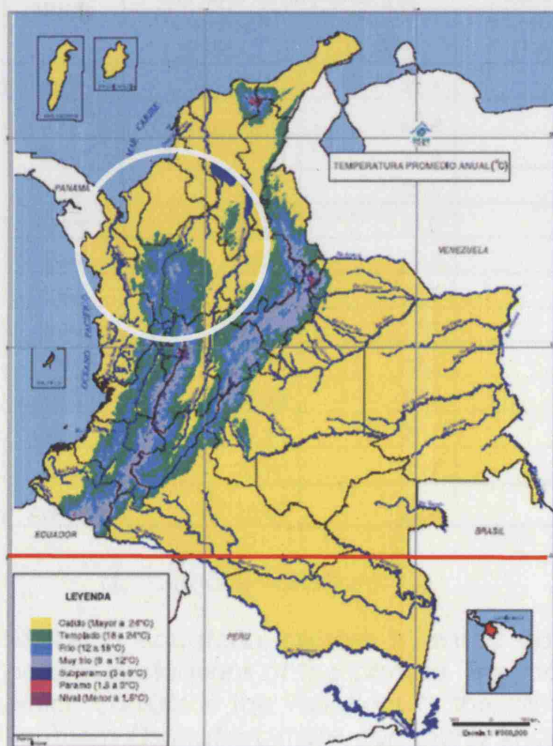
In the tropical countries, the factor that determinates the temperature is the altitude. The decrease in the mean temperature of the air as the altitude increases is known as the thermal floors. With every 1000 metres of altitude, the temperature decreases by 6.5°C.

Approximate temperatures at different altitudes.				
ALTITUDE (m)	MIN. Mean Temp. (°C)	MEAN Temp. (°C)	MAX. Mean Temp. (°C)	Thermal Floors
0 - 499	23.4	28.2	33.2	Hot
500 - 999	20.7	25.4	30.5	
<b>1000 - 1499</b>	<b>17.9</b>	<b>22.6</b>	<b>27.7</b>	Temperate
1500 - 1999	15.2	19.8	25	
2000 - 2499	12.4	17	22.2	Cold
2500 - 2999	9.7	14.2	19.5	
3000 - 3499	6.9	11.4	16.7	Páramo <sup>51</sup> (High Plateau)
3500 - 3999	4.2	8.6	14	
4000 - 4999	1.4	5.8	11.2	Snowcapped

**Table 04:** Temperature Description at different heights showing the thermal floor. The colours showed in this table are referred to graphs 18 and 1.

Colombia (see graph 19) is located where the Andean range spreads out in three chains. It benefits from a great variety of climates and biodiversity. This is particularly relevant because most of the population lives in the Andean region, like Medellín.

Medellín is located in the valley of the river Aburrá, at an altitude of 1.490<sup>52</sup> metres above sea level. It has an annual mean temperature of 22°C (2005). (See table 05 that also contains general information about the climate)



**Graph 19:** Map showing the thermal floors in Colombia in Medellín and Antioquia

**Graph 20:** Map showing the thermal floors in Medellín and Antioquia

<sup>51</sup> Páramo is a neotropical andean ecosystem. It is located in the high Andes region, between the upper forest line (about 3500 m altitude) and the permanent snow line (about 5000 m). The ecosystem consists of varying topography; mostly glacial valleys and plains with a large variety of lakes, peat bogs and wet grasslands intermingled with shrub lands and forest patches.

<sup>52</sup> Measurements taken in the Meteorological station Olaya Herrera Airport, located within the city of Medellín.



Medellín COLOMBIA, METEOROLOGICAL STATION OLAYA HERRERA <sup>53</sup>									
YEAR 2005    Altitude: 1490 m    Longitude: -75.60    Latitude: 6.22 N									
Month	Mean Temperature			Absolute Temperature		Relative Humidity	Sunlight	Precipitation	Evaporation
	Max	Min	Mean	Max	Min	%	Hours	mm	
JAN	27.7	16.5	22.1	31.6	12.4	66	175.5	61.4	135.6
FEB	28.0	16.6	22.3	33.0	12.4	66	149	76.1	121.6
MAR	28.0	17.0	22.5	33.4	13.0	67	154.2	120.6	130.6
APR	27.6	17.3	22.5	32.8	13.9	70	127.9	163.1	121.8
MAY	27.4	17.0	22.2	32.2	12.8	71	138.9	199.5	114.7
JUN	27.9	17.0	22.5	32.0	10.4	67	173	147.7	125.9
JUL	28.3	16.7	22.5	32.0	10.0	63	203.2	118.9	148.3
AUG	28.2	16.8	22.5	33.6	11.4	65	191.6	154	147
SEP	28.0	16.4	22.2	33.1	10.2	69	153.4	171.7	123.5
OCT	27.0	16.8	21.9	31.3	11.2	72	132.9	221	106.7
NOV	27.0	16.3	21.7	31.1	11.2	73	136.4	151.1	103.0
DEC	27.1	16.3	21.7	32.9	10.9	70	156.2	87.8	109.7
Annual	27.7	16.7	22.2	32.4	11.7	68.3	157.7	139.4	125.9

Table 05: Meteorological data taken in the station airport Olaya Herrera<sup>54</sup>

For the purposes of this study, the mean temperature and relative humidity of 1995 were also taken into account as they represent two recorded variations.

Month	Dry Bulb Temperature [C]		Relative Humidity [%]	
	Meteonorm (1995)	IDEAM (2005)	Meteonorm (1995)	IDEAM (2005)
JAN	20.62	22.1	75.97	66
FEB	20.82	22.3	75.97	66
MAR	20.84	22.5	75.00	67
APR	20.46	22.5	75.98	70
MAY	20.36	22.2	70.02	71
JUN	20.29	22.5	65.99	67
JUL	20.56	22.5	62.99	63
AUG	20.55	22.5	63.98	65
SEP	20.25	22.2	66.03	69
OCT	19.80	21.9	72.99	72
NOV	19.81	21.7	78.99	73
DEC	20.11	21.7	78.00	70
Annual	20.40	22.2	71.80	68.3

Table 06: Comparative table of temperatures taken by Meteonorm (1995) and IDEAM (2005).<sup>55</sup>

#### d. Climate Variations:

Although equatorial climate is almost constant, it has some anomalies. They refer to the natural fluctuations of the climate. The most transcendental fluctuation is Annual Variability, which consists in the variations of the climate from year to year. One such anomaly is the Southern Oscillation, more commonly known as the "El Niño" and "La Niña" phenomenons.

<sup>53</sup> and <sup>54</sup> Data provided by IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia) from the meteorological station Olaya Herrera.

<sup>55</sup> Meteotest. Meteonorm 5.x: Global Meteorological Database for Solar Energy and Applied Meteorology. [http://www.meteotest.ch/en/mn\\_home?w=ber](http://www.meteotest.ch/en/mn_home?w=ber)

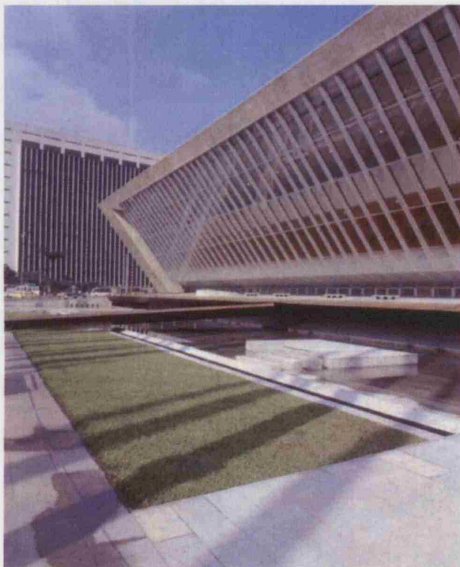
The "El Niño" phenomenon occurs when the surface water of the Pacific Ocean becomes hotter in the cost of Peru, Ecuador and Colombia than in the rest of the tropical Pacific. This warming of the surface water is very extensive and affects the weather. For example, it dramatically increases evaporation rates, bringing torrential rain to western-tropical South America.

### 3.1.2. Building description:

The building used for this analysis was the EPM Public Library, which is located in the Medellín city centre. It was built as part of a city centre renovation project that took place in 2004 and has been in use since 2005. One of the reasons why the building was chosen was the fact that it is a public building, which is used during hours when the sun is available. Another reason is that it was conceived as a passive solar design building.

#### a. Passive solar design: Bioclimatic Strategies used

The basic design of the public library is based on the structure of pyramids. It is distributed in three levels, which are planned to go from the general to the specialized areas. The total area of the project is 15.829 m<sup>2</sup>, including the urban spaces. However, the building has a total built-up area of 8,500 m<sup>2</sup>; 3,085m<sup>2</sup> of which are located in the basement, 2,215m<sup>2</sup> on the ground floor and 3,200 m<sup>2</sup> on the first floor. The library has different levels and voids that make the design very dynamic and integrated. These ideas can be appreciated in the following pictures:



PIC 07: External view (east façade) of the public library



PIC 08: Internal view of the public library

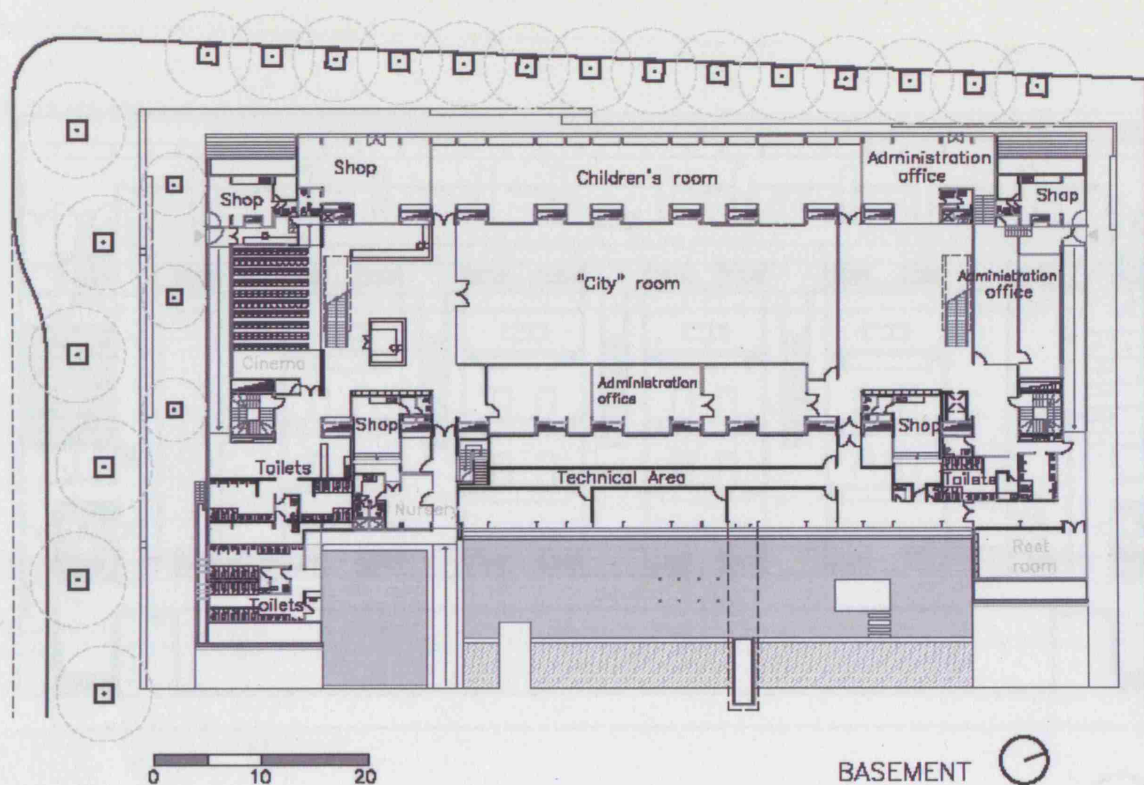


PIC 09: Internal view. Information counters.

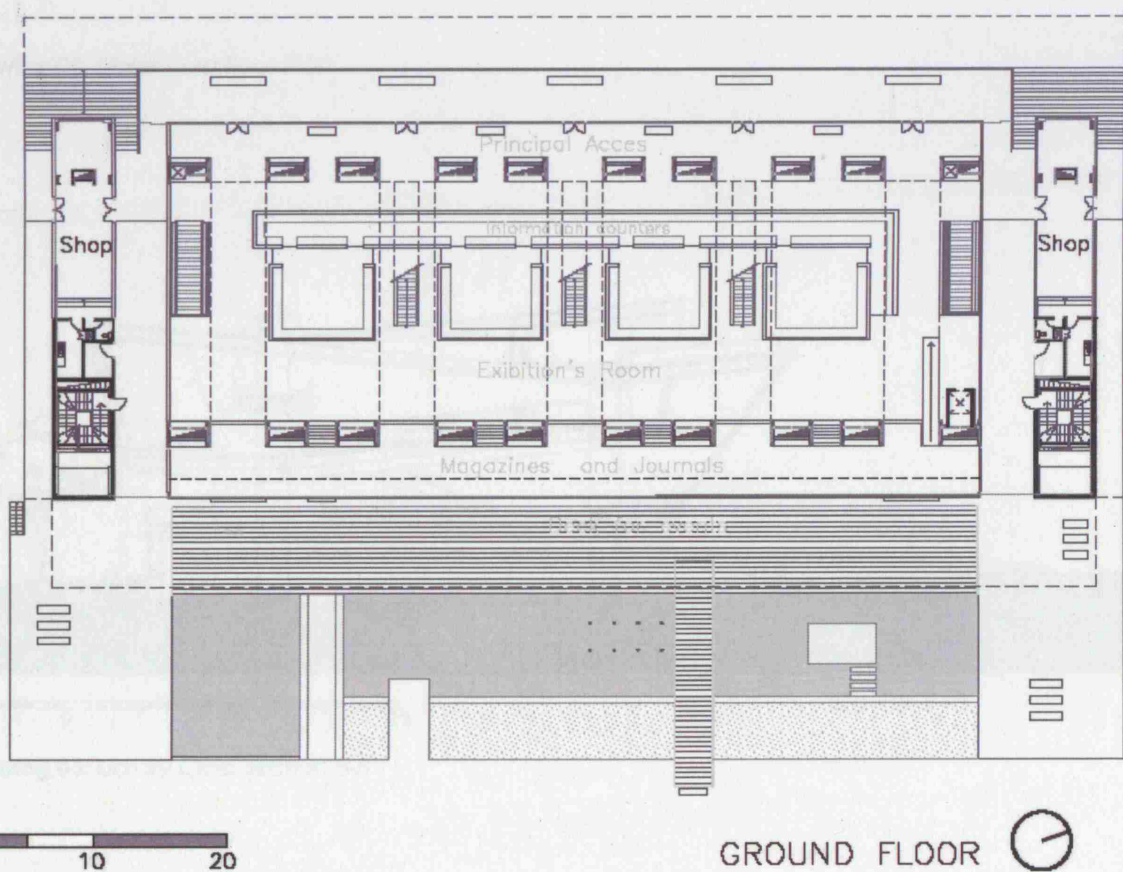


PIC 10: Internal view east side



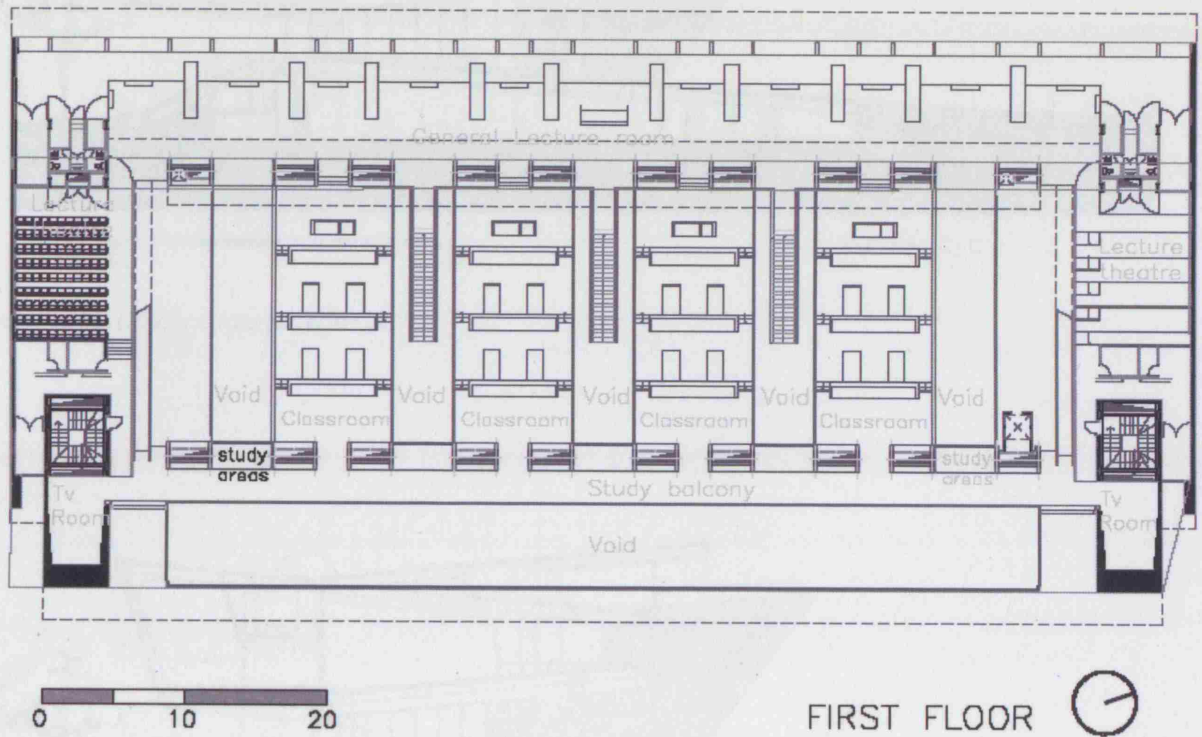


Drawing 01: Library Basement Plan

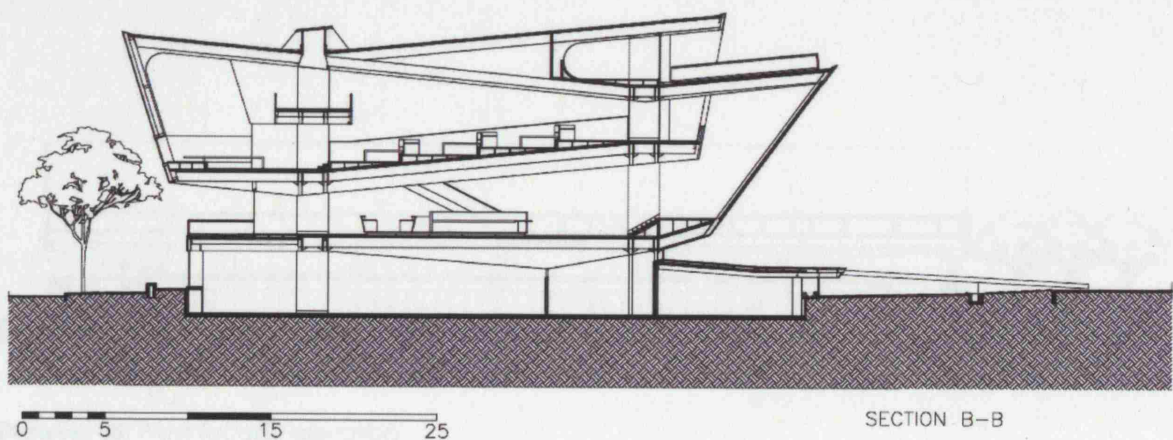


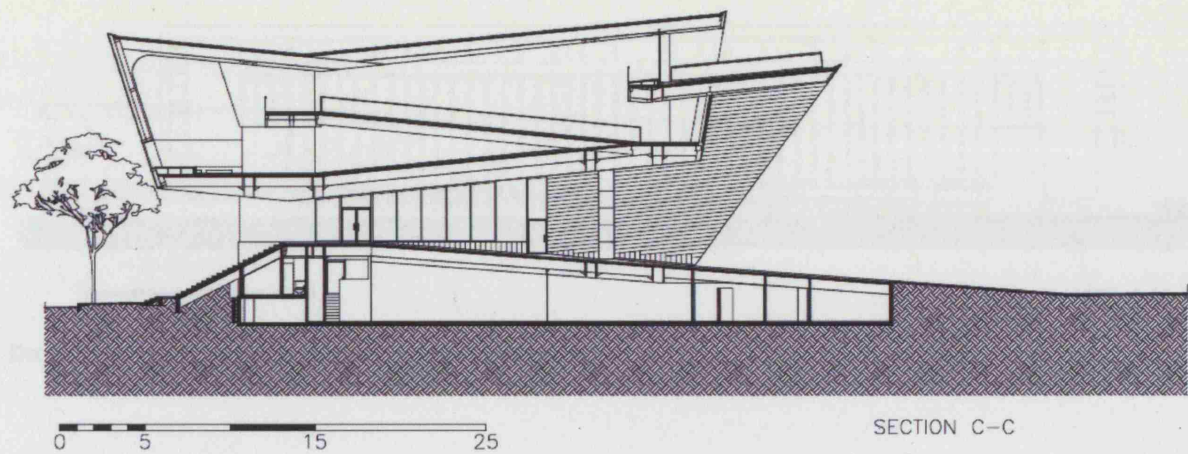
Drawing 02: Library Ground floor Plan



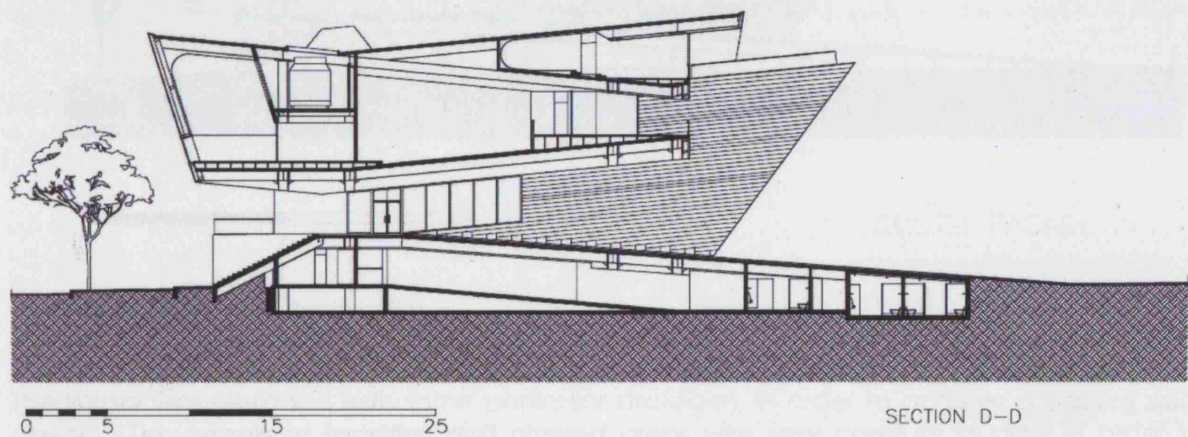


Drawing 03: Library First floor Plan

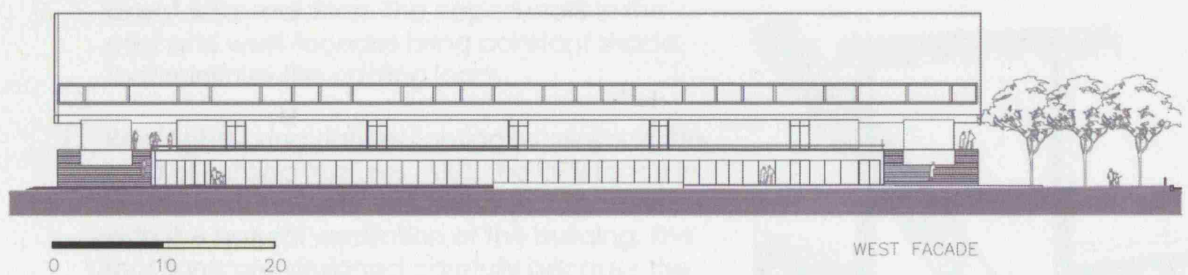




**Drawing 06:** Library Cross section C-C'

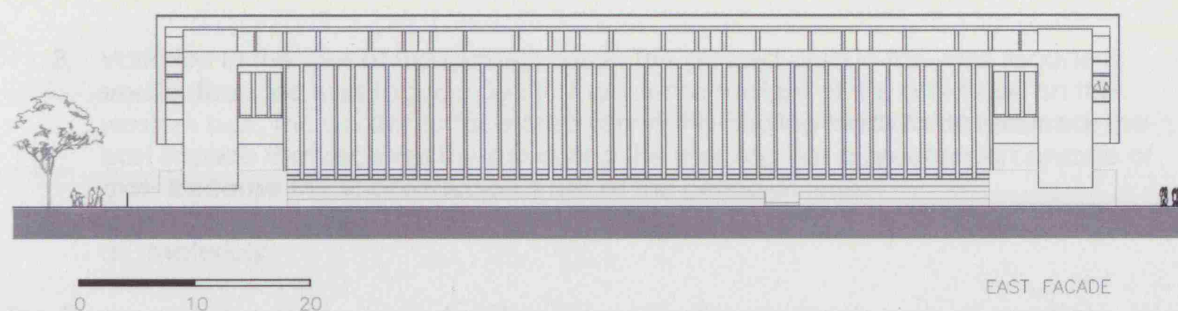


**Drawing 07:** Library Cross section D-D'

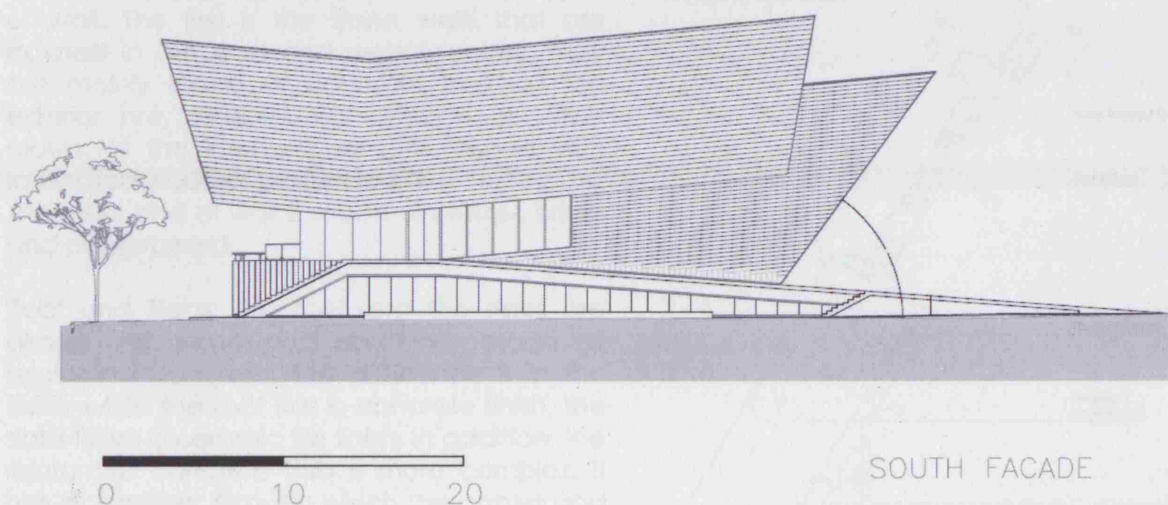


**Drawing 08:** West façade elevation





**Drawing 09:** East façade elevation. Main entrance.



**Drawing 10:** South façade elevation

The library was designed with some particular strategies, in order to achieve a passive solar design. The system of façades and glassed areas was very carefully studied in order to provide internal comfort to the occupants. The orientation and the solar control were important, not only for the internal comfort but also for the energy efficiency of the library. The main strategies are explained as follows:

1. The most important façades and the ones that needed a carefully planned design were the east and west façades that receive direct solar radiation. The sloped walls in the east and west façades bring constant shade that minimize the cooling loads.
2. Roof lights bring natural lighting to minimize the load of lighting features. Also, the difference in height and the openings in the roof lights help with the natural ventilation of the building. The roof lights are designed carefully because the light that gets into the library is not direct. (see drawing 11)

**Drawing 11:** Roof light detail.





3. Variation in the sizes of the glassed areas: The glassed area in the west façade is smaller than the east façade due to the intense sunlight of the afternoon on the western side. The smaller surface area allows the cooling loads to be reduced. The east façade that receives the sun during the morning has a greater percentage of glass because the solar radiation is less at this period of time.

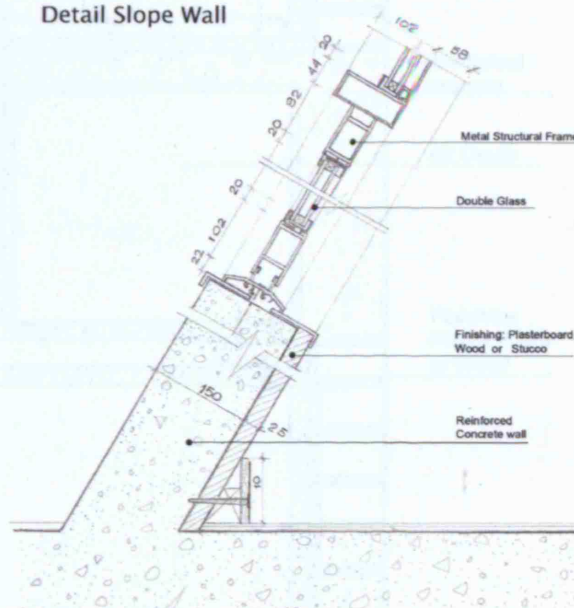
a. Materials:

The library was constructed with traditional construction materials such as concrete, brick, wood and glass. The materials used are described and illustrated as follows (from exterior to interior):

**Walls:** In the building, there are two main types of wall. The first is the slope walls that are located in the east and west façades. They are mainly made of concrete and on the exterior are covered with stucco or stone plates. In the interior they are finished with laminated wood or plasterboard. The other kind of wall is made of plaster, bricks and plasterboard.

**Roof and Slabs:** The roof and the slabs are almost the same and are both made of reinforced concrete. The difference is in the finish; whilst the roof has a concrete finish, the slabs have a ceramic tile finish. In addition, the reinforced concrete slab is more complex. It has air cavities, through which the cables and pipes go and the false ceiling is encased in plasterboard.

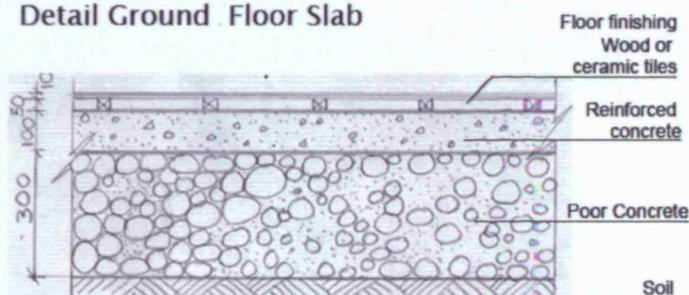
Detail Slope Wall



Drawing 12: Detail Slope wall, showing double glazing used in east façade

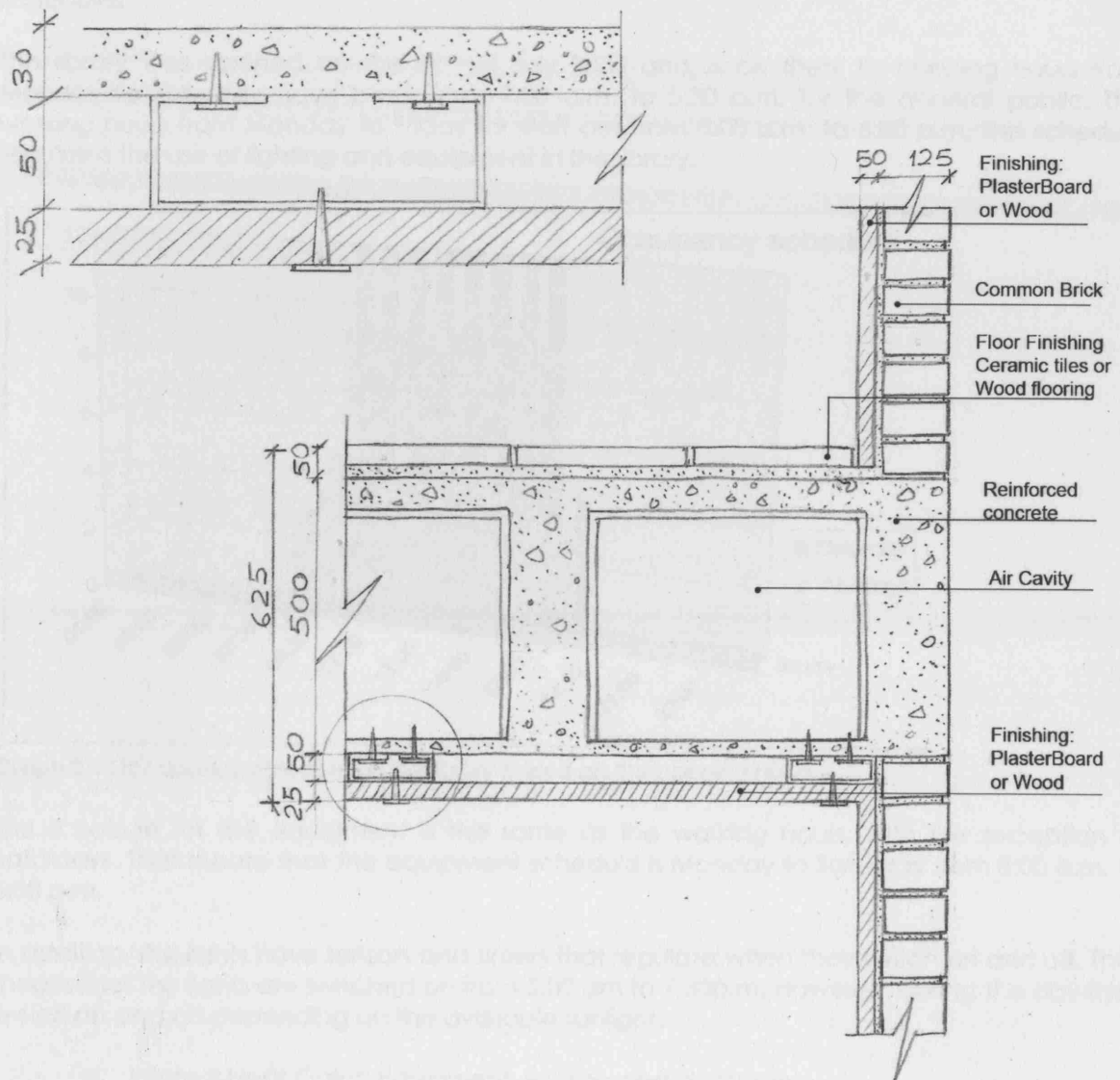
Detail Ground Floor Slab

**Ground floor:** It has a substantial portion of soil, which is covered by poor concrete with reinforced concrete on top. Finally, it is covered with laminated wood flooring or ceramic tiles.



Drawing 13: Detail Ground floor slab.

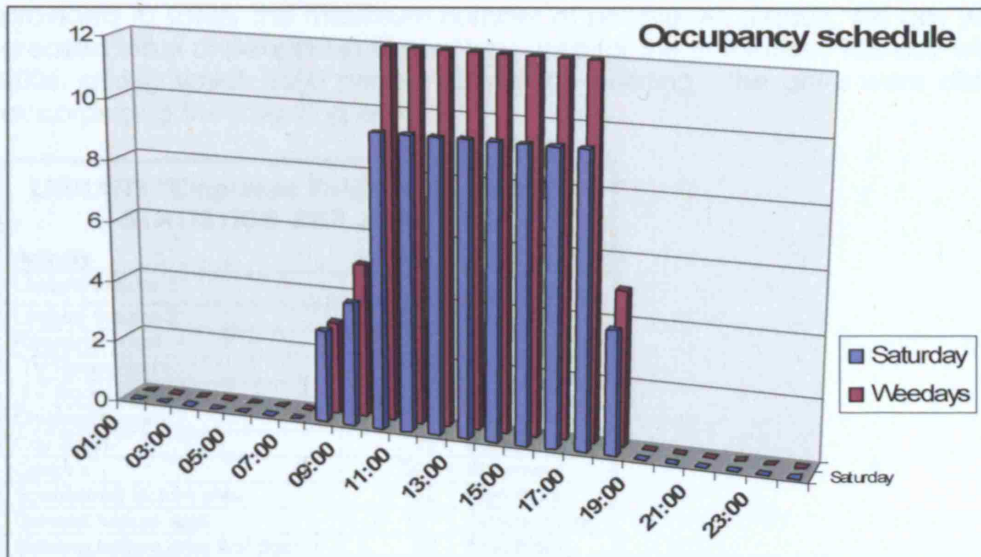
**Glassed areas:** The windows are made from single glass panes and structural metal frames. The only windows that are double-glazed are the ones in the east because they cover a large area and receive a large amount of solar radiation.



**Drawing 14:** Detail slabs and south and north walls

### Schedules

The library was opened on the 11<sup>th</sup> of July 2005 and since then, its opening hours from Monday to Saturday have been from 9:00 a.m. to 5:30 p.m. for the general public. The working hours from Monday to Friday for staff are from 8:00 a.m. to 6:00 p.m. This schedule regulates the use of lighting and equipment in the library.



**Graph 21:** Occupancy schedule of the library based on the opening hours

The schedule for the equipment is the same as the working hours, with the exception of Saturdays. That means that the equipment schedule is Monday to Saturday from 8:00 a.m. to 6:00 p.m.

In addition, the lights have sensors and timers that regulate when they switch on and off. That means that the lights are switched on from 5.00 am to 7.30p.m. However, during the day they switch on and off depending on the available sunlight.

#### b. Internal Heat Gains: Equipment, lighting and occupancy

##### Equipment:

Currently, the building has approximately 200 units of equipment. They are classified as 80% PCs, and 10% in televisions, video beam projectors and audio and video equipment and 10% photocopiers.

In a building, about 50% of internal loads are caused by office equipment such as PCs (typically 150W including the monitor), printers (190 W for laser printers, 20 W for inkjets), photocopiers (1100 W) etc., which leads to an area-related load of about 10-15 W/m<sup>2</sup>.

##### Lighting:

As explained previously, the lighting devices are influenced by the intensity of the sunlight. Nevertheless, the internal gains for lighting were calculated depending on the type of luminarie. 40% of the lighting devices are compact fluorescent lights, 30% fluorescent luminaries and 30% are metal halide luminaries (circulation areas). The minimum illuminance requirement for a library is 500 luxes, based on the CIBSE guide A, which also determined 14 W/m<sup>2</sup> for compact fluorescent, 11W/m<sup>2</sup> for fluorescent and 18W/m<sup>2</sup> for Metal Halide devices. This data is also comparable with the book SOLAR.... that suggests that a "modern office lighting has a typical connected load of 10-20 W/m<sup>2</sup> at an illuminance of 300-500 lx".



### Occupancy:

The number of people that have visited the library has been recorded and registered since it opened last year. Taking into account these records, the internal gains produced by the influx of people were calculated. The average daily influx of people was not used because the simulation has to be done allowing for the fact that on any given day there could be substantially more people than the average and therefore it is essential that enough energy is provided to satisfy the maximum number of people. As a result, the day when there was the greatest influx of people up till now was used for the simulation. This day was the 29th of June 2006, during which 1500 people visited the building. The gains were distributed as follows, according to the following areas:

LIBRARY "Empresas Publicas de Medellín" STATISTICS 29th JUNE 2006		
Activity	USERS	AREA
Lecture theatre 1	80	First Floor
Lecture theatre 2	20	First Floor
Research room	48	First Floor
TV Room North	15	First Floor
TV Room South	0	First Floor
Children's room	167	Basement
City Room	25	Basement
Cinema	200	Basement
Specialized lecture area	32	First Floor
General lecture area	131	Ground Floor
General lecture area first floor	98	First Floor
Audio and video room	19	First Floor
Internet room	591	Ground Floor
Specialized rooms	23	First Floor
Offices	20	Basement
Guided Walks (Around Library)	35	Ground Floor
<b>TOTAL</b>	<b>1504</b>	

**Table 07:** Number of users during June the 29th, day of higher occupancy in June.

To calculate the heat gains produced by the people, this figure was multiplied by 115 Watts. This assumption was made according to CIBSE guide A that says that a person that is "seated, carrying out very light work or walking" emits 115 Watts of heat energy. From it, 70W corresponds to sensible energy and 45W to latent energy.

Degree of activity	Typical building	Total rate of heat emission for adult male / W	Rate of heat emission for mixture of males and females / W			Percentage of sensible heat that is radiant heat for stated air movement / %	
			Total	Sensible	Latent	High	Low
Seated at theatre	Theatre, cinema (matinee)	115	95	65	30	—	—
Seated at theatre, night	Theatre, cinema (night)	115	105	70	35	60	27
Seated, very light work	Offices, hotels, apartments	130	115	70	45	—	—

**Table 08:** Typical rates which heat given off by humans. Source CIBSE Guide A.

#### c. Internal conditions: Air conditioning and Infiltration rate

Currently, the library is working with conventional air conditioning devices that are switched on before or when the library is opened to the public (7.30a.m or 8 a.m.) and is switched off depending on the internal temperature or when it is closes. The operating temperatures for air conditioning are between 19°C to 24°C.

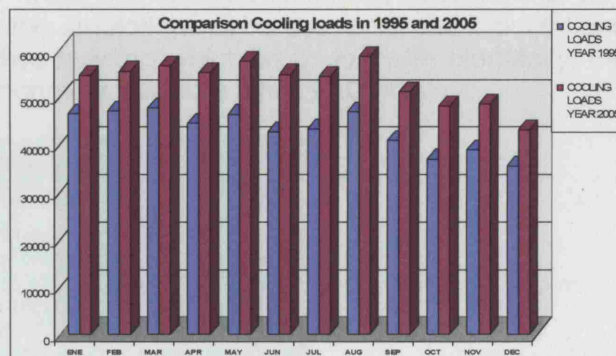
The infiltration rate was calculated based on the number of people and the minimum requirement of air 10 l/s per person. As a result, the total air changes caused by infiltration and ventilation are 0.42m<sup>3</sup>/s for the basement, 0.72m<sup>3</sup>/s for the ground floor and 0.34m<sup>3</sup>/s for the first floor. The total for the whole building is 1.46m<sup>3</sup>/s.

### 3.1. Simulation

#### 3.1.1. Energy consumption:

Taking into account all the features of the building, a simulation was carried out to find out the energy consumption of the library. For this, the following methodology was applied:

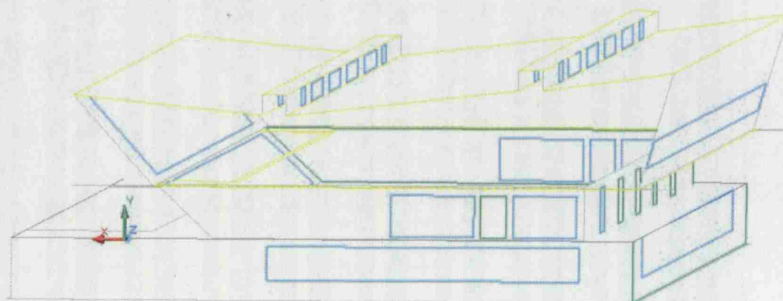
1. The building case study was modelled in the computer program Energy Plus (EPlus)<sup>50</sup>.
2. Then, all the characteristic of the building were put into the same computer program as detailed previously (weather data, internal gains, infiltration rate, materials, etc...). The weather file used was base on the data from Meteonorm (1995) and IDEAM (2005).



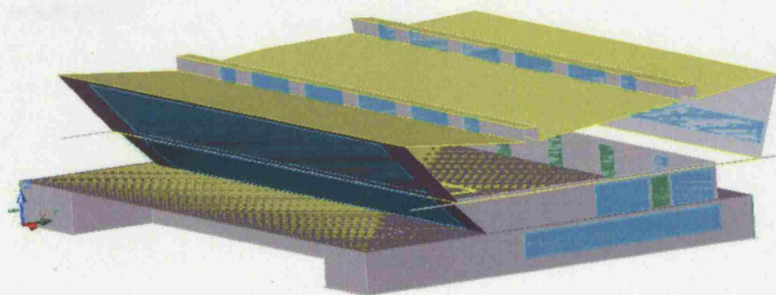
**Graph 22:** Average of the monthly cooling loads. It shows how different weather files affect the loads of the building.

3. After that, a simulation of the building was run on the computer program Eplus.
4. The energy consumption of the building was then obtained and subdivided into cooling loads, heating loads and equipment and lighting consumption.

For the simulation, the building was divided into two zones: the basement (zone 1) and the ground and first floors (zone 2). Zone 2 included two floors because they share the same internal conditions due to the number of voids on the first floor. The model was done in keeping with the shapes of the building but simplified them as much as possible. The following drawing illustrates the building form after it was modelled.



**Drawing 15:** 3D Model of the library done in Eplus, showing the two different zones of the building.



**Drawing 16:** North east view of 3D Model of the library done in Eplus.

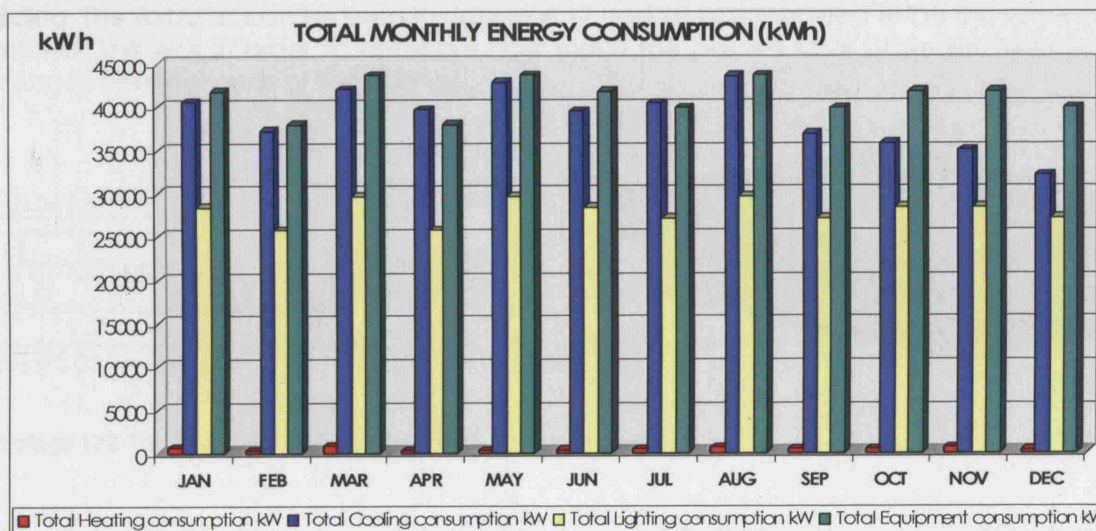
<sup>50</sup> Eplus, Energy Simulation Program. Energy Efficiency and Renewable Energy. U.S Department of energy. (Building energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows).



After the simulation, the cooling loads that are shown in the following graph were obtained. This is distributed in heating loads, cooling loads, lighting and equipment consumption. In the library, during the whole year, there are no noticeable heating loads. On the contrary, the peaks of cooling loads, which are presented in June, are 139.51 kWh. The total annual energy consumption is 828,770.80 kWh, which is distributed in: heating 1,893.47 kWh, cooling 145,469.05 kWh, lighting 335,306.40 kWh and equipment 493,464.40 kWh. As a result the monthly average is 81,186.65 kWh. Comparing this data from the simulation with the last energy consumption of the current building, which was 95,045 kWh for July 2006<sup>51</sup>, it was very accurate, and for this reason the data from the simulation will be use for all the calculations. Comparing this data with a typical civic office building which works just with electricity, the library is catalogued as a Good Practice benchmark because it has 92.08 kW/m<sup>2</sup>.

Energy benchmarks for local authority buildings (annual consumption for net lettable area)			
Design area	Application	Other information	Rule of thumb
Town hall	Electricity consumption	Good practice Typical	84 kWh/m <sup>2</sup> 111 kWh/m <sup>2</sup>
	Fossil fuel	Good practice Typical	112 kWh/m <sup>2</sup> 170 kWh/m <sup>2</sup>
Air conditioned civic offices	Electricity consumption	Good practice Typical	97 kWh/m <sup>2</sup> 178 kWh/m <sup>2</sup>
	Fossil fuel	Good practice Typical	128 kWh/m <sup>2</sup> 226 kWh/m <sup>2</sup>

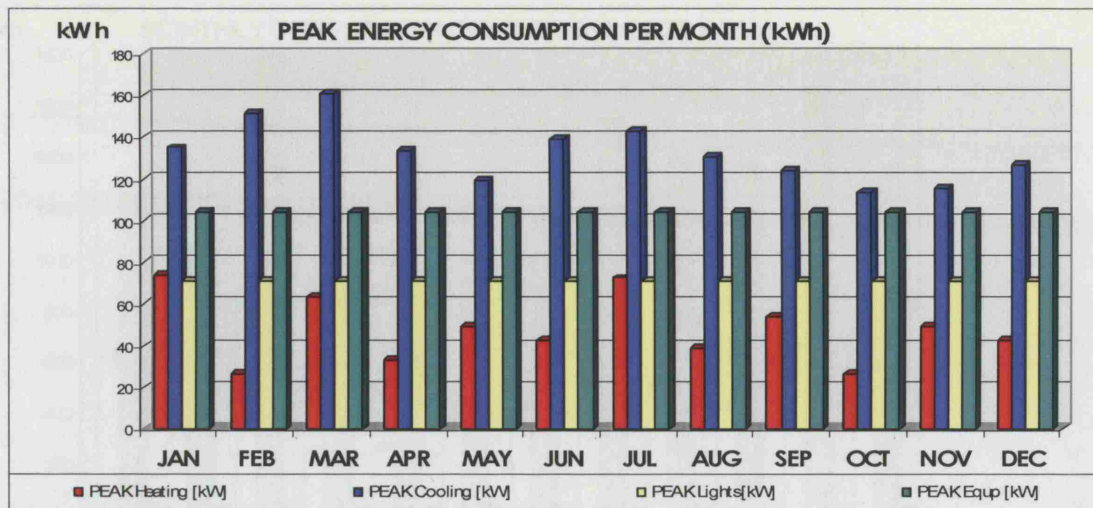
**Table 09:** .Energy benchmarks for local authority buildings. Source: A BSRIA Guide: Rules of Thumb (4th edition)



**Graph 23:** Total monthly consumption in kWh showing each category (heating, cooling, lighting and equipment)

<sup>51</sup> Data given by Empresas Públicas de Medellín. August 2006

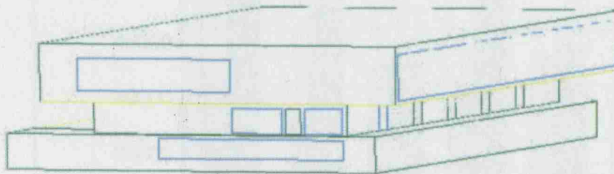




**Graph 24:** Peak energy consumption per month in kWh, detailing each category (heating, cooling, lighting and equipment).

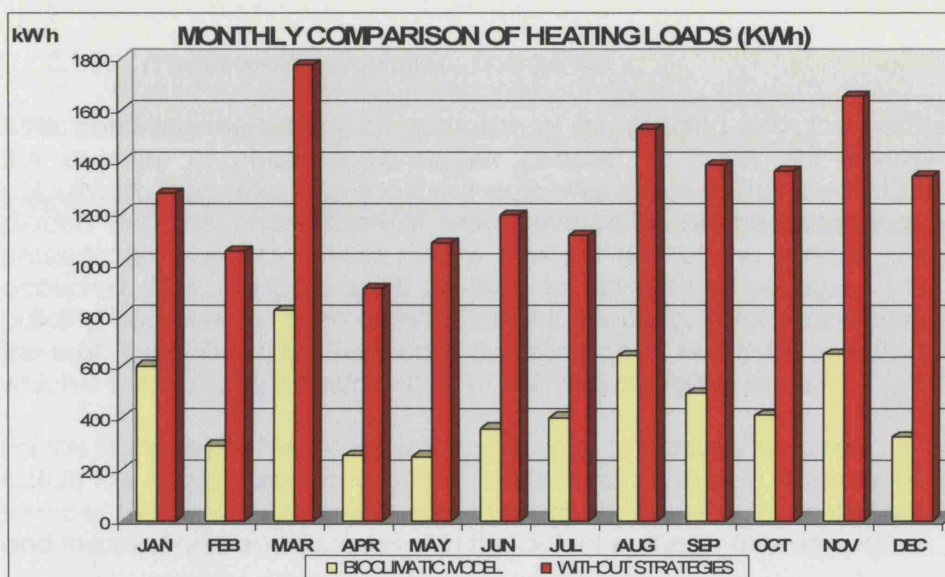
### 3.1.2. Passive solar comparison

Having obtained the energy consumption of the building, it was modelled again, but in this case, the passive solar strategies were excluded and it was simulated as a conventional building. The form, as can be seen in drawings 17 and 18 was modified to be the same as the materials. This was in order to compare how much the passive solar strategies reduced the cooling or heating loads of the building.



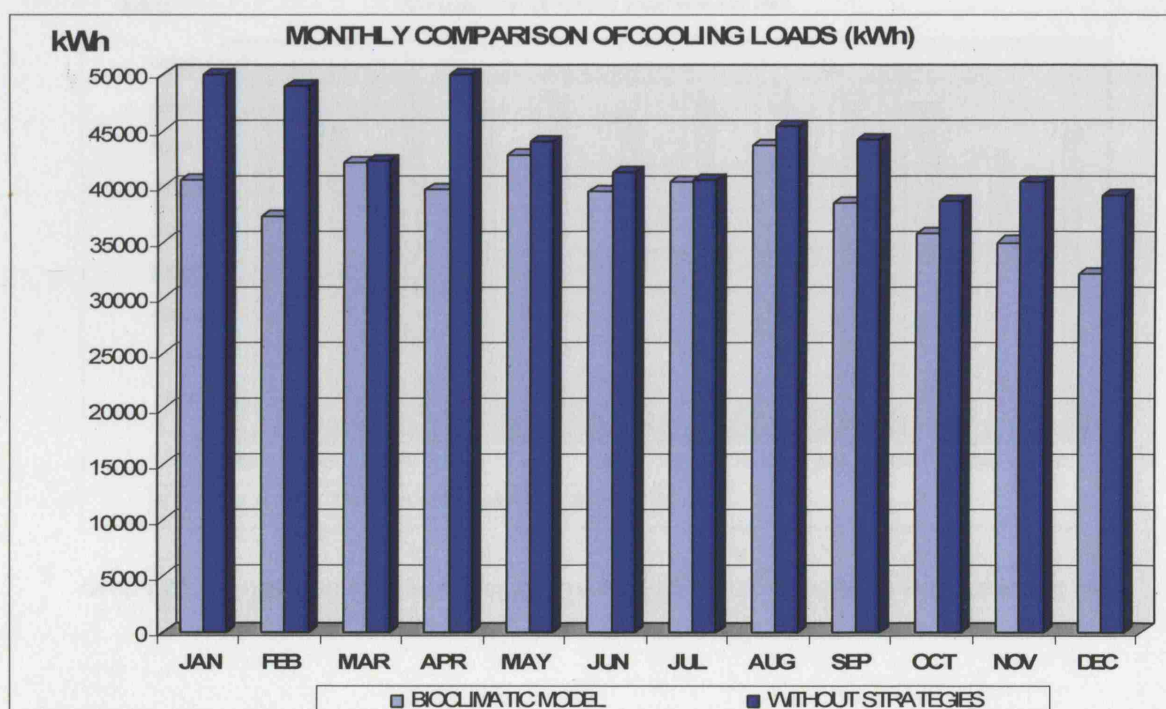
**Drawings 17& 18:** 3D Model without the passive solar strategies.

Although the heating loads are depreciable compared with the other loads of the building, for this specific comparison, the heating loads were taken into account. As shown in graph 25, the building without the strategies has more heating loads compared to the real building. The month with higher consumption is March, when the heating loads for the building without strategies reached 1,772.77 kWh, compared to 818.72 kWh for the building that incorporates the strategies.



**Graph 25:** Comparison of the monthly heating loads between the building with and without the passive solar strategies.

The cooling loads, which are very important for this study, were also compared, showing that the building without strategies performed worse than the current building. While the conventional building demonstrated cooling loads of near 50,000 kW in January, the peak for the current building was about 40,000 in August. During the whole year, the loads of the building without strategies were higher as it doesn't prevent the excess of solar gains, so it can't save energy that is then required for cooling.



**Graph 26:** Comparison of the monthly cooling loads between the building with and without the passive solar strategies

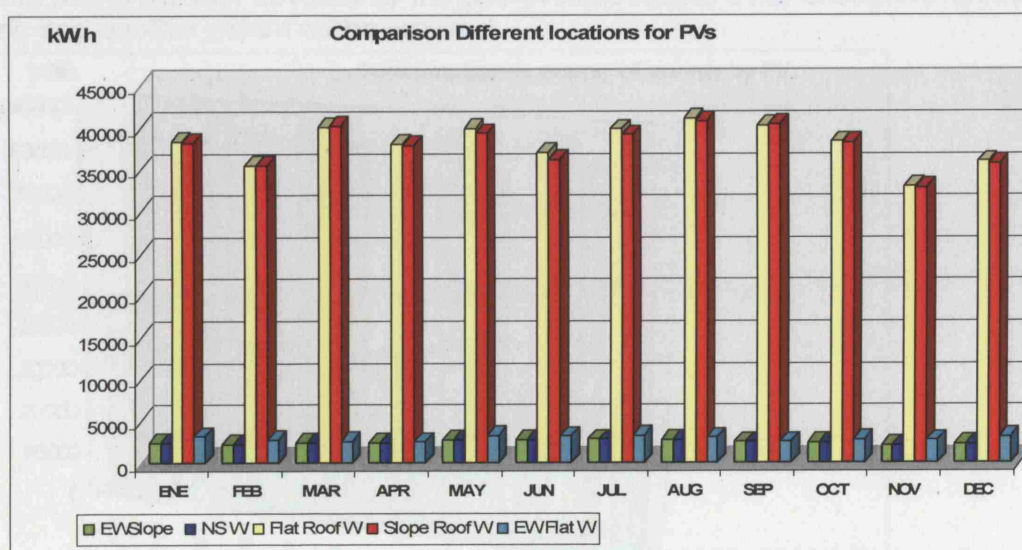


### 3.1.3. Photovoltaic calculation: EnergyPlus

After obtaining the energy consumption of the building from the computer program EPlus, the quantity of photovoltaic panels needed to cover this energy consumption was calculated. Then, the following input data was entered: The area where it was going to be placed and the percentage of area covered. In all the cases that were analysed, this percentage was 50%, which means that just half of the surface area was going to be occupied. Also, the panels will be fixed to the surface because in this specific case, the building had already been constructed. For example, instead of placing the solar panels on the roof, they had to be fixed on it, elevating costs. Finally the eventual efficiency was 0.12, which is the average efficiency for PVs with polycrystalline panels.

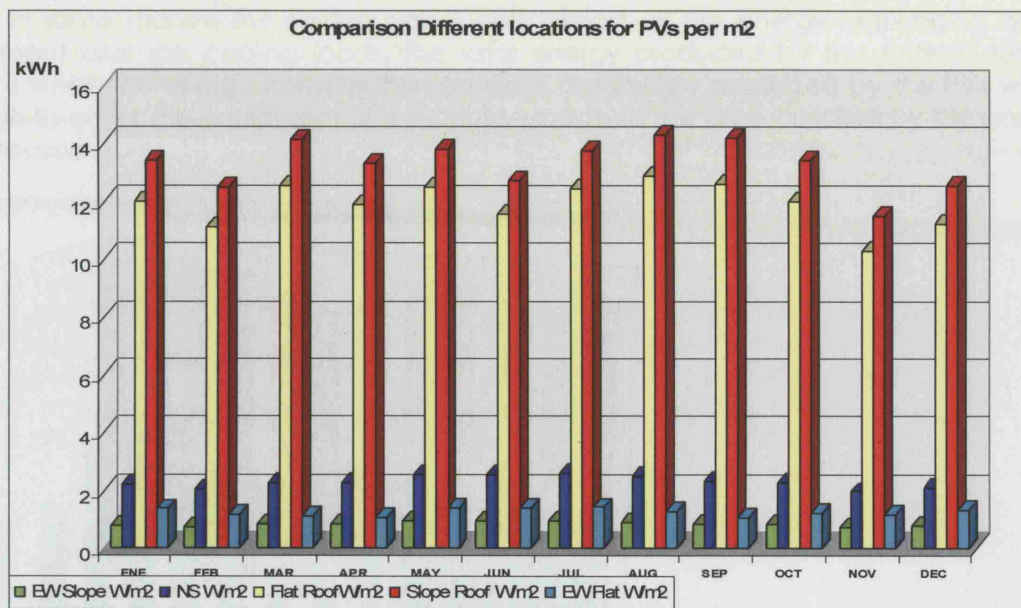
For the first analysis, the PV system was applied to different surfaces. This was done in order to obtain the energy produced by the photovoltaic system in different locations. The different surfaces tested were the walls and the roof. All the walls were analysed in vertical position and the west and east façades with the actual wall inclination as well.

In the roof two options were evaluated, one with the flat roof and the other with the sloped roof. In general, it is better to install the photovoltaic panels in the roof rather than on the surface. As can be seen in graph 27, the photovoltaic panels located on the roof produce more than twenty times more electricity than the ones on the walls. This is not only caused by solar radiation but also by the size of the area where they are placed. A comparison of the energy produced by  $\text{m}^2$  of photovoltaic is shown in the graph 28. In this graph it is clear that one  $\text{m}^2$  of PV placed on the sloped roof produces up to 14 kWh in august, compared to the sloped wall that produces 1W per hour.



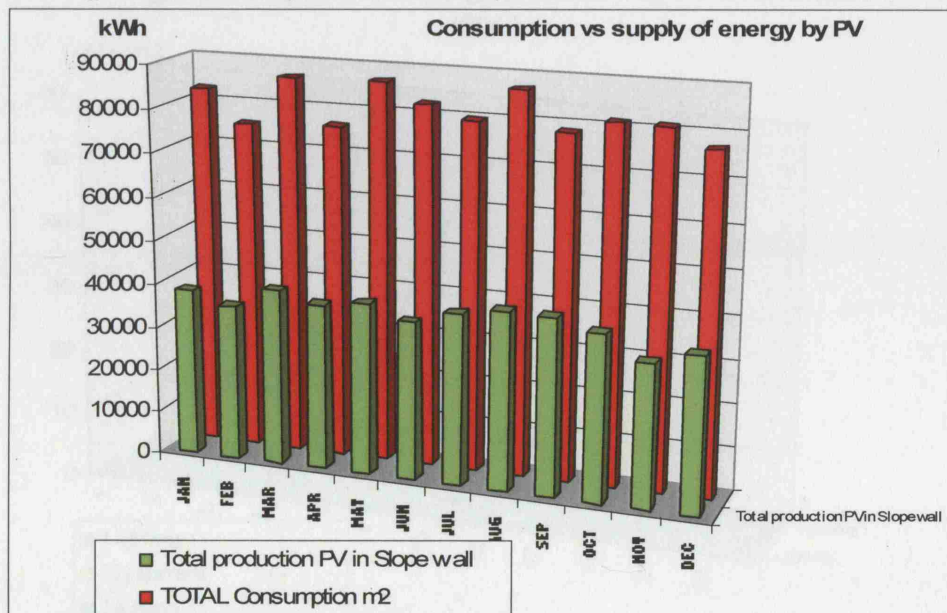
Graph 27: Comparison of different locations of photovoltaics Monthly energy produce (W)





**Graph 28:** Comparison of different locations of photovoltaics monthly energy produce per square metre ( $W/m^2$ )

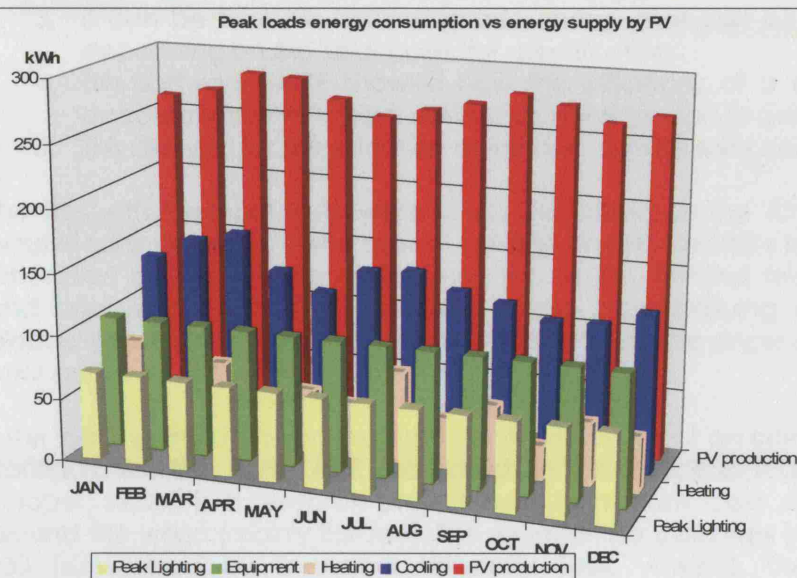
In conclusion, the best location for the photovoltaic panels is the sloped roof, which has an inclination of  $6^\circ$  facing east and west. Now, the consumption of the building is going to be compared with the energy production of the photovoltaic panels located on the sloped roof. In graph 29, the energy produced by the photovoltaic panels (green bars), produces 40,888.22 kWh (in August) of the total energy required to run the building. Therefore, it is clear that with 50% of the roof covered by the photovoltaic system is not enough to run the whole building and another system will be required.



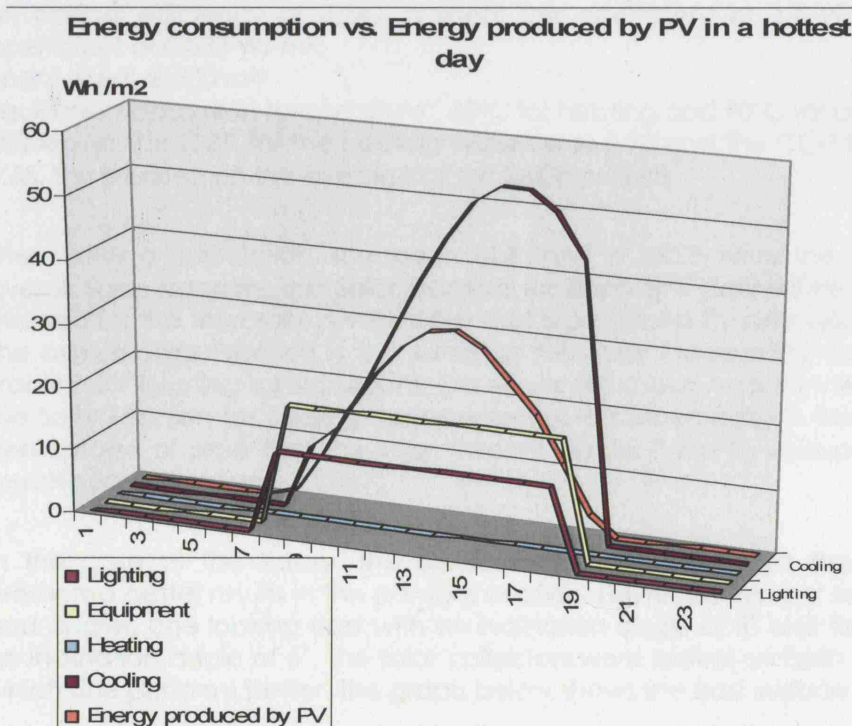
**Graph 29:** Comparison between the energy consumption of the building and the energy supply by the photovoltaics with a 50% of roof coverage.

In addition, the consumption is shown separately to know what proportion of the load the photovoltaic panels can cover. In graph 30, it is shown that all the peak loads can be covered separately. The lighting and the equipment can be covered completely by the photovoltaics. The other option is to cover either the equipment or the cooling loads.

Whilst in some months the system can supply almost all the energy required to drive the equipment and the cooling loads, the total energy produced by the system during the months when the energy consumption exceeds the energy produced by the PVs won't be enough to cover the equipment or the cooling loads, so the area covered by the panels has to be increased.



**Graph 30:** Comparison between the peak loads of the building and the energy supply by the photovoltaics with a 50% of roof coverage



**Graph 31:** Comparison between the energy consumption of the building and the energy supply by the photovoltaics with a 50% of roof coverage)

In graph 31, energy consumption during the hottest day is shown against the energy generated by the panels. It is clearly shown that the energy produced by the panel is not covering the totality of the cooling loads that the building is producing.



Active Solar Cooling: Software SACE<sup>52</sup>

1. The obtained results of the energy consumption were used to create the input files that were introduced into the computer program SACE.
2. SACE then calculated the solar fraction cooling, which is the percentage of total cooling load provided by the solar radiation.
3. It can be then be converted into energy that can be used by the cooling system, depending on the solar collector specifications.
4. The software SACE showed how the efficiency of a solar cooling system varies in accordance with its heat storage capabilities and its collector efficiency.
5. This allowed for the selection of the appropriate solar cooling system for the library.

The files with the input data were hourly files based on the 3D model that presented all the passive solar strategies in the current building. The file contains the following data:

Operation of the building, airflow needed ( $\text{m}^3/\text{h}$ ), internal and external temperatures ( $^{\circ}\text{C}$ ) and relative humidity (%), cooling, heating, dehumidifying and humidifying loads ( $\text{Wh}$ ), global, diffuse and total solar radiation ( $\text{Wh}/\text{m}^2$ ) and the angle of incidence of the sun on the solar panel.

After loading this data, an example configuration file of an office from SACE was used. These configuration files from SACE are based on the European Project 'Solar Air Conditioning in Europe', which is a research project based on many case studies that use these systems around the world (mainly Europe). The example file used was MERIDOFF.LMF: Office building, 930 (developed by Technical University Graz, Austria). The following information was introduced:

*Collector type:* AOSol\_CPC\_1.5X. This refers to the flat evacuated tubes solar collector. It has an optical efficiency of 0.940, a linear loss coefficient of  $2.2 \text{ W}/\text{m}^2$  and a quadrant loss coefficient of  $0.033 \text{ W}/\text{m}^2$ .

*Room area:*  $8,500 \text{ m}^2$

*Equipment operation temperature:*  $45^{\circ}\text{C}$  for heating and  $90^{\circ}\text{C}$  for cooling.

*Efficiency:* The COP for the heating system was 0.98 and the COP for the thermal chiller was 0.65. This is based on the average of the SACE project.

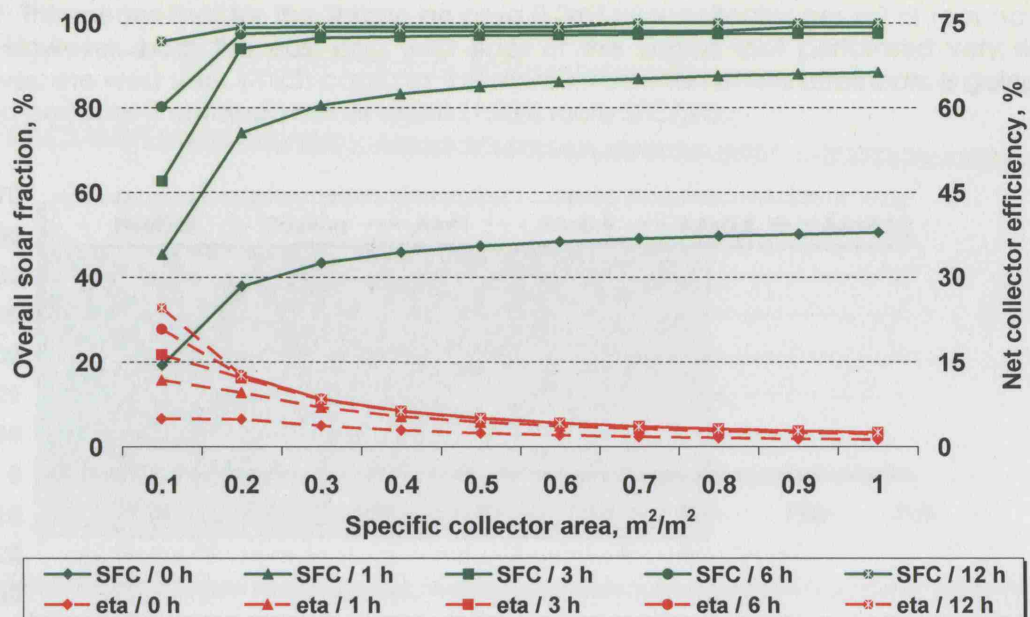
Then, after a calculation, the results obtained in SACE were the cooling, heating and the overall Solar Fraction. The Solar Fraction for cooling is defined as "the fraction of the heat needed for the thermally driven chiller that is produced by solar energy". In this specific case, the overall Solar Fraction is the same as the Solar Fraction for Cooling because the Solar Fraction for Heating is insignificant. The results are shown with the net collector efficiency and the Solar Fraction for cooling (represented as a percentage) in the y-axis. In the x-axis is the percentage of area that the solar thermal panels have to occupy in order to provide the specific Solar Fraction.

In the case of the library, the collectors are positioned on the sloped roof because it presented better results in the previous analysis. However, this roof has two different directions and angles, one looking east with an inclination angle of  $5^{\circ}$  and the other looking west with an inclination angle of  $6^{\circ}$ . The solar collectors were tested on both surfaces in order to know which one performs better. The graph below shows the east surface result:

<sup>52</sup> SACE. Solar Air conditioning in Europe. European Commision Research doctorate general. <http://www.ocp.tudelft.nl/ev/res/sace.htm>

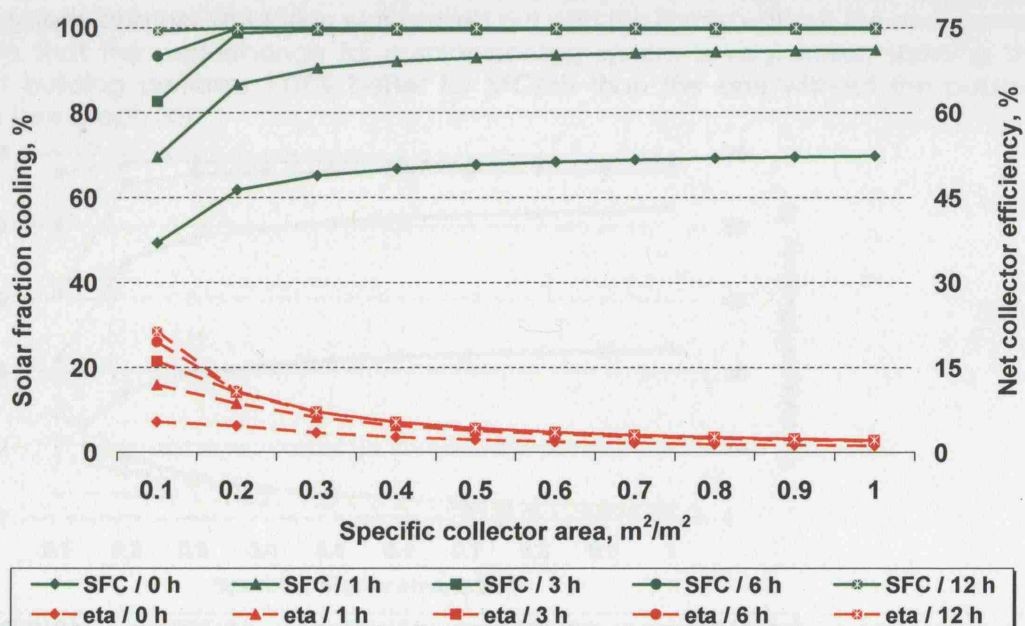


EAST



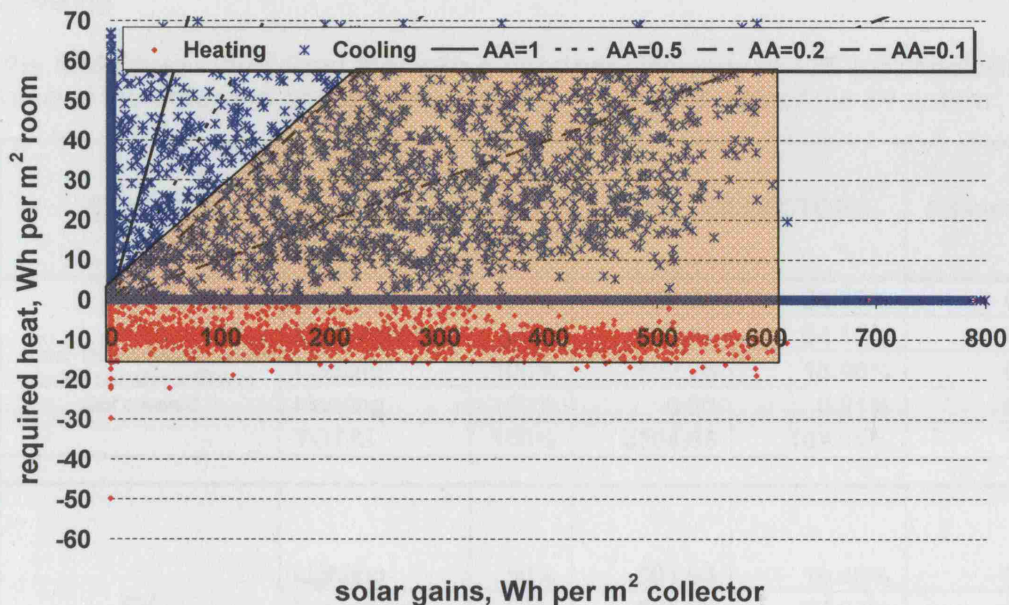
Graph 32: Result of solar cooling system oriented east.

In the graph above, the green lines represent the Solar Fraction for Cooling which is the percentage of cooling obtained with the heat produced by the solar panels. It also varies depending on the heat storage. For example, SFC/1h is the solar fraction produced with a collector capacity of  $1\text{ kWh}/\text{m}^2$ , which can cover 1 hour of peak cooling loads. Eta/1h means the efficiency of the when it can store one hour heat after the sun is no longer available. The more the heat storage or the collector capacity increases, the more expensive the system is. Also, the more efficient the system is, the greater the surface area it has to occupy. In conclusion, for this specific case of the library, locating the panels in the east side of the sloped roof and covering just  $0.2\text{ m}^2/\text{m}^2$ , a SFC from 38.51% (0 hours of storage) to 99.86% (12 hours of storage) can be obtained. Nevertheless, a good performance (95.47%) can be obtained with heat storage of 3 hours and  $3\text{ kWh}/\text{m}^2$  of collector capacity.



Graph 33: Result of solar cooling system oriented west

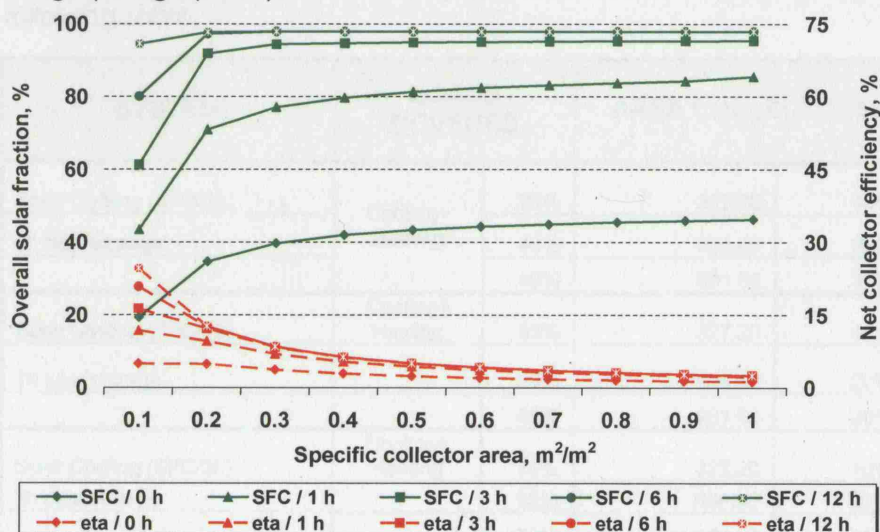
These results can be compared with the solar collectors located on the west surface, which show a better performance because for SFC/3h, 98.27% can be obtained in an area of 0.2 m<sup>2</sup>/m<sup>2</sup>. This means that for the library, an area 0.2m<sup>2</sup> solar collector per m<sup>2</sup> of roof has to be used. However, both the east and west sides of the sloped roof performed very similarly. However, the west side, which captures the more intense sun of the afternoon, is going to be chosen because it obtained better results (1.03% more SFC/3h).



Graph 34: Hourly loads against solar gains.

The graph above shows the hourly-required heat for the cooling against the pure solar gains. As a consequence, for the specific case of the library, if an area of 0.2m<sup>2</sup>/m<sup>2</sup> is going to be used, the area in orange is the heat that the solar collectors can provide to the system. In conclusion, the system is covering the majority of the heat required just by being driven by the sun.

Moreover, in order to compare and see how a solar passive design affects the performance of this system, another simulation was carried out with the library without the design strategies. It shows that the performance for a solar cooling system is very similar, showing that the current building performs 1.07% better for SFC/3h than the one without the passive solar design (see graph 35).



Graph 35: Result of solar cooling system in the building without passive solar strategies.



### 3.2. Comparison:

It is important to underline the fact that buildings driven by solar energy perform much better when they are using combined systems. For this study, different comparisons were made in order to develop the best combination for the building in study. The variables that are going to be taken into account are the area, the efficiency of the systems and the loads they are covering.

The table below described that with a constant efficiency of 12% (polycrystalline panels) the area of the collectors changed depending on the coverage of the PV system.

SYSTEM	LOADS COVERED		AREA COLLECTORS		Efficiency
PV Note: The simulation was carried out with a 50% of roof covered	Lighting	100%	1203.87	36.79%	0.12
	Equipment	100%	1771.71	54.15%	0.12
	Cooling	100%	522.28	15.96%	0.12
	Heating	100%	6.80	0.21%	0.12
	<b>TOTAL</b>	<b>100%</b>	<b>3504.66</b>	<b>107.11%</b>	
PV	Lighting	50%	601.93	18.40%	0.12
	Equipment	50%	885.85	27.07%	0.12
	Cooling	50%	261.14	7.98%	0.12
	Heating	50%	3.40	0.10%	0.12
	<b>TOTAL</b>	<b>50%</b>	<b>1752.33</b>	<b>53.56%</b>	
PV	Lighting	25%	300.97	9.20%	0.12
	Equipment	25%	442.93	13.54%	0.12
	Cooling	25%	130.57	3.99%	0.12
	Heating	25%	1.70	0.05%	0.12
	<b>TOTAL</b>	<b>25%</b>	<b>876.16</b>	<b>26.78%</b>	

**Table 10:** Comparison of Photovoltaic system changing the area covered by the panels.

After obtaining the results, the cooling systems taken into account are described in the following table.

SYSTEM	LOADS COVERED		AREA COLLECTORS		Efficiency
Solar Cooling (SFC/0h)	Cooling+ Heating	25%	327.20	10%	0.2503
0h heat storage		44%	654.40	20%	0.4358
		49%	981.60	30%	0.4855
Solar Cooling (SFC/1h)	Cooling+ Heating	55%	327.20	10%	0.5515
1h heat storage		80%	654.40	20%	0.8030
		86%	981.60	30%	0.8606
Solar Cooling (SFC/3h)	Cooling+ Heating	74%	327.20	10%	0.7446
3h heat storage		98%	654.40	20%	0.9827
		99%	981.60	30%	0.9917

**Table 11:** Comparison of Solar cooling system changing different variables (efficiency, storage, area).



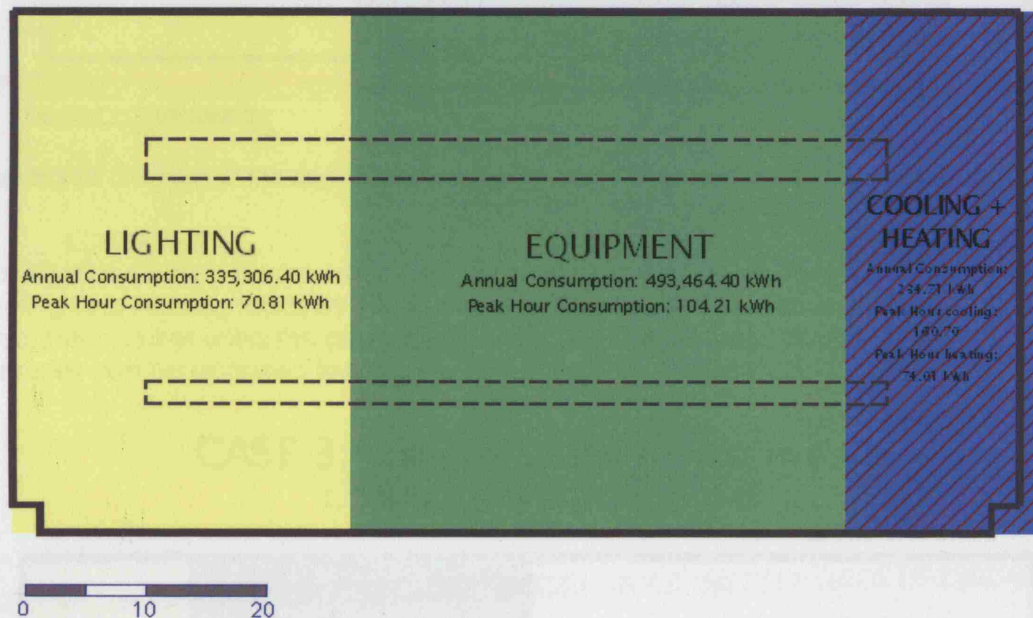
### 3.2.1. Different Combinations of Active solar technologies:

After knowing the areas and the loads covered by the different systems, some combinations were carried out in order to find out the right one for the case study. Consequently, four cases are shown as follows.

#### a. CASE 1

Case 1 is showing a building run 100% by the photovoltaic system. The area covered by the panels is 3504.66 m<sup>2</sup>, which represents 107% of the roof area. For this reason some panels have to be displayed in another place in order to achieve an auto sustainable library that produces its own electricity.

### CASE 1: PV SYSTEM 100% COVERED

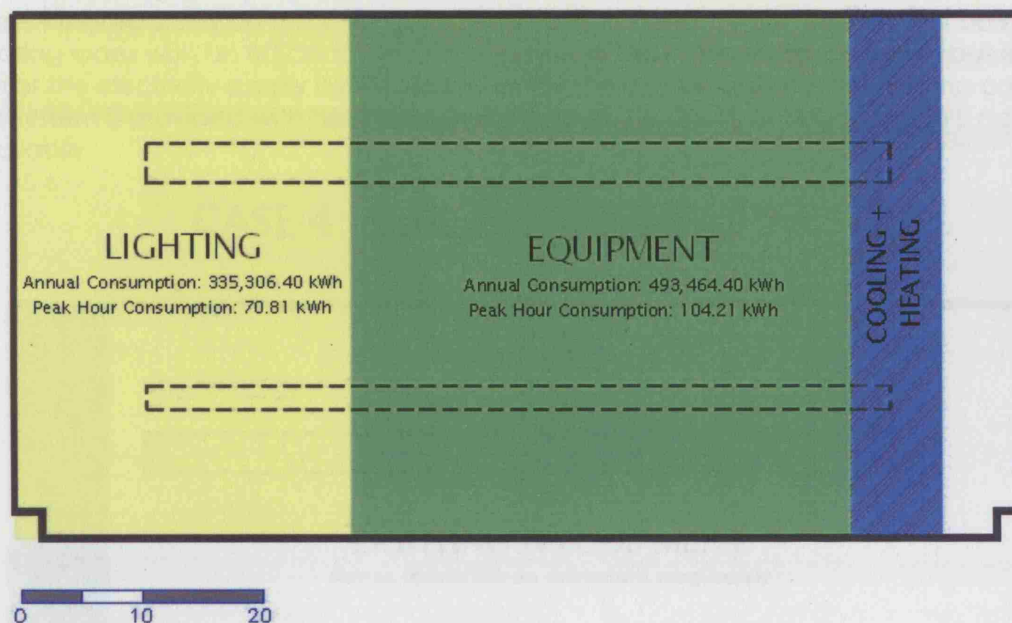


Drawing 19: Diagram of the slope roof showing the area cover for Case 1.

#### b. CASE 2

Case 2 is based on a combined system which covers 100% electric loads and the cooling and heating loads with an efficiency of 74%. This system uses 90% of the roof area and does not require the use of the electricity supply from the grid, because it can cover 100% of the building consumption. In addition, when the sun is not available it has heat storage of 3 hours and for the photovoltaic system, batteries can be acquired to store electric energy.

## CASE 2: COMBINED SYSTEM 100% ELECTRIC AND COOLING AT 74%

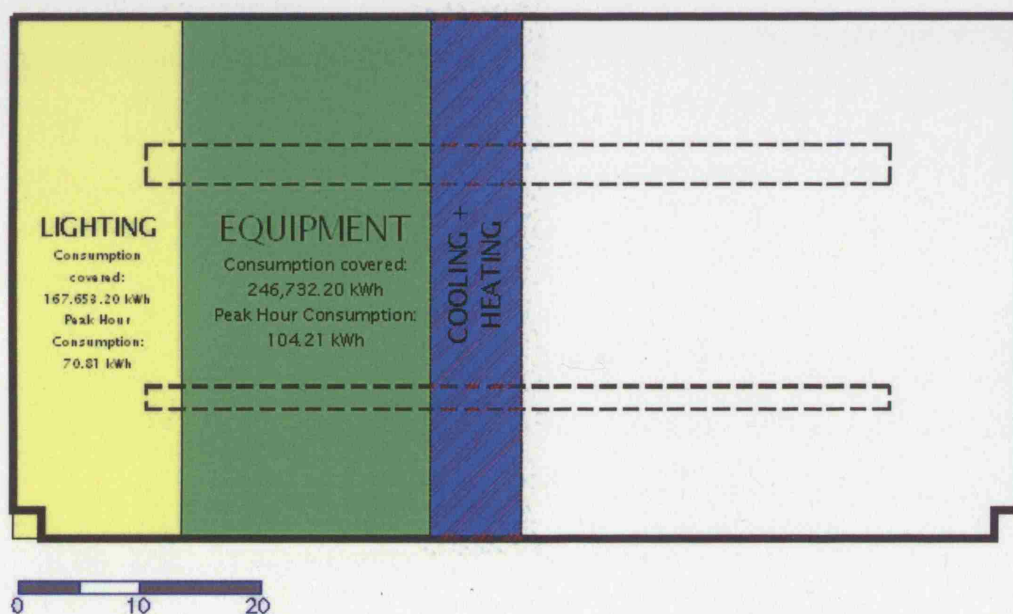


Drawing 20: Diagram of the slope roof showing the area cover for Case 2.

### c. CASE 3

Case 3 is also based on a combined system that covers 50% of the electric loads and the cooling and heating loads by 100%, with an efficiency of 74%. This system uses 46% of the roof area, but requires using the grid supply. As in case 2, it has heat storage of 3 hours and batteries can be acquired to store electric energy for the photovoltaic system

## CASE 3: COMBINED SYSTEM 50% ELECTRIC AND COOLING WITH EFFICIENCY 74%



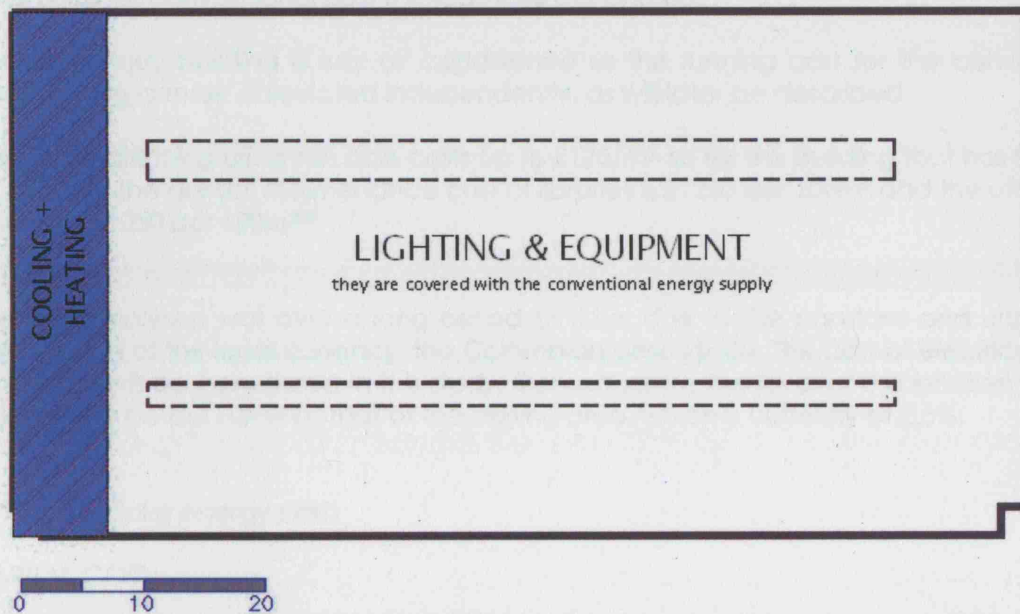
Drawing 19: Diagram of the slope roof showing the area cover for Case 3.



## d. CASE 4

Case 4 is based only on the solar absorption cooling system. It just covers the cooling and heating loads with an efficiency of 74%. This system uses 10% of the roof area, but requires the use of the electricity supply by the grid to cover the equipment and the lighting consumption. This system is provided with heat storage for 3 hours, for the time when the sun is not available.

## CASE 4: COOLING WITH EFFICIENCY 74%



Drawing 19: Diagram of the slope roof showing the area cover for Case 4.

### 3.3. Economic Study:

The costs of various technologies for solar energy will be compared to that of the conventional electric supply.

#### 3.3.1. Cost conventional supply:

The cost of the conventional electric supply for this study consists only of the running cost required to satisfy the building demand. It is equal to 974,239.85 kWh per year at \$col 212 per kWh, which at the exchange rate corresponds to £ 0.0475 per kWh. As a result, the current total price for conventional cost is **£ 46,276.40** per annum.

The case study building is fully air conditioned so the running cost for the conventional air conditioning can be calculated independently, as will later be described.

Full air conditioning using fan coils costs up to £175/m<sup>2</sup>, so for this building that has 8500 m<sup>2</sup> it is £1,487,500. The annual maintenance cost of libraries is £1250 per 100m<sup>2</sup> and the utility cost per annum is £1050 per 100m<sup>2</sup><sup>53</sup>

The cost analysed was over a long period of time, due to the constant and unpredictable devaluation of the local currency, the Colombian peso (\$col). The cost of electrical energy in Colombia will be considered in this study. Consequently, the level of the inflation will also be assumed to be the same as that of the sterling area, which is currently at 2.5%.

#### 3.3.2. Solar energy cost:

##### CAPITAL COST:

The cost of solar energy, for the purpose of this study is only the capital cost, reducing the running cost to nil. The financial factor will not be considered.

This is calculated as follows:

$$K = (p \times m^2) + d + c;$$

Where:

K = Capital cost  
(p x m<sup>2</sup>) = m<sup>2</sup> of solar panel  
d = device  
c = batteries

##### a. Photovoltaic system:

$$K_{pv} = (p \times m^2) + ch + b + c$$

Where;

K<sub>pv</sub> = Photovoltaic system Capital cost  
p = Panel  
m<sup>2</sup> = Area covered by solar panels 2326m<sup>2</sup>  
ch = Charger Controller  
i = Inverter  
b = Batteries

<sup>53</sup> Rule thumbs



Prices of Photovoltaic System in US\$		
Element	Cost in USA	Cost in Colombia
Panel	\$5.45/Wp	\$6.5/Wp
Charger Controller	\$5.8/Amp	\$7.5/Amp
Inverter	\$0.70/W cont	\$0.84/Wcont
Batteries (optional)	\$1.65/Wp	\$1.71/Wp

**Table 12:** Prices in \$US of the PV devices of the PV system display in USA and Colombia.

The table above shows the prices of each element when on display in the United States and in Colombia. When the batteries are used on the system, the charger controller is usually required.

The prices of the system are based on the peak load of cooling in which the cooling system is going to operate. In order to calculate it, it was necessary to use this formula:

The peak load of cooling in which the system is working is: 160.70 KWh

$$PVsize = \frac{\text{Total annual BC}}{SI * t * \text{Inv Eff} * \text{Losses}}$$

Where; PVsize = the size of the photovoltaic system [kWp]  
 BC = Total annual Building consumption [kWh]  
 SI = Solar Intensity (on the best day 1kW per m<sup>2</sup>) [kW/ m<sup>2</sup>]  
 t = Average sun peak hours per day (4.5h in Medellín) [h]  
 InvEff = Inverter Efficiency  
 Losses = Losses in wiring

PV size = 486.44 kWp

Element	US Price US \$	US Price converted in GBP £	Colombian Price US \$	Colombian Price converted in GBP £
Panel (Wp)	\$2,651,124.80	£1,420,912.75	\$3,161,891.97	£1,694,666.58
Charger Controller (Amp) *	\$19,592.92	£10,501.14	\$25,335.67	£13,579.06
Inverter (W cont)	\$342,943.67	£183,806.14	\$407,835.42	£218,585.92
Batteries (Wp)	\$802,634.11	£430,184.59	\$831,820.81	£445,827.67
<b>TOTAL PV 100% covered</b>	<b>\$3,816,295.50</b>	<b>£2,045,404.63</b>	<b>\$4,426,883.87</b>	<b>£2,372,659.23</b>

<b>PV size (kWpeak)</b>	<b>486.44</b>
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**Table 13:** Calculation showing the cost of the PV system display in USA and Colombia.

\*Moreover, to calculate the charger controller the following formula: Watts = Volts x Amp

#### b. Solar Cooling System:

$$Ksc = (p * m^2) + HVAC + h$$

Where;

Kpv = Photovoltaic system Capital cost  
 p = Solar Collectors  
 m<sup>2</sup> = Area covered by the solar collectors  
 HVAC = HVAC System, which is composed by  
 1. Absorption water machine  
 2. Piping  
 3. Controller  
 h = heat water storage

It was calculated according to the options discussed in the last chapter.

#### Solar Collectors:

The solar collectors used are evacuated tube collectors, which cost up to \$400 per m<sup>2</sup>

#### HVAC System:

It is composed of the Absorption water machine, piping and the controllers.

The costs are: \$4,000 - \$8000 per TR<sup>54</sup>  
 \$4,500 per TR<sup>55</sup>  
 € 4012 per TR = \$ 5084 per TR<sup>56</sup>

To convert into TR the following conversions were used:

1 TR = 12,000 BTU hr                      and                      1 BTU hr = 0.293 W

so, 1 TR = 3.516 kW

The peak load during the year is 160.70 kWh

To calculate the TR, the peak load is multiplied by the percentage that the system is going to cover, which will be 90% because the amount of time that the system reaches this peak is not very extensive and the system does not have to be designed for a peak load that is only a few hours a day.

Therefore,  $160.7 \times 0.9 / 3.516 = 41.13 \text{ TR}$

If the price of \$4000 per TR is taken the HVAC system for the absorption chiller is going to cost \$164,539.25

#### Heat Storage:

Heat storage		
heat loss coefficient	Wm <sup>-2</sup> K <sup>-1</sup>	0.8
maximum storage temperature	°C	98
specific costs	€/m <sup>3</sup>	600

**Table 14:** Heat storage costs. Source: SACE Economic Report

The heat storage was calculated making some assumptions about the system using the following formulae:

Power = flow rate x  $\Delta T$  x Thermal Capacity of water

In which,  $\Delta T$  will be assumed to be 10°C and the thermal capacity of the water is 4.1 kJ/kg °C

Where Power p = Nominal power / 0.9 Efficiency of the system.

Power p = 144.63, which is the nominal power peak of the machine.

Flow rate = Power Water input /  $\Delta T$  x Thermal Capacity of water

<sup>54</sup> Sourcebook for green and sustainable building. [www.green-builder.com](http://www.green-builder.com)

<sup>55</sup> California Energy Commission. [www.energy.ca.gov](http://www.energy.ca.gov)

<sup>56</sup> SACE: **Initial Cost:** The overall system cost [(excluding pipe / duct network from system to application and application equipment (e.g. fan coils, induction units)] divided by the installed cooling capacity: Average value of solar cooling (reviewed projects SACE) 4012 €/kW. LiBr/H<sub>2</sub>O lowest costs is 3102 €/kW.



Flow rate = 3.83 kg/s

As a result,

For storage of 1h it will be at **13.78 m<sup>3</sup>** of full capacity

And for storage of 3 hours it will be at **41.36m<sup>3</sup>** of full capacity.

The table below shows the results of the previous calculations:

SYSTEM	LOADS COVERED		AREA COLLECTORS		Efficiency	COST				
						Panels	System	Heat Storage	US Price US \$	US Price converted in GBP £
Solar Cooling (SFC/0h) 0h heat storage	Cooling+ Heating	25%	327.20	10%	0.2503	\$130,880.00	\$45,760.64	\$0.00	\$176,640.64	£94,673.37
		44%	654.40	20%	0.4358	\$261,760.00	\$79,674.33	\$0.00	\$341,434.33	£182,997.19
		49%	981.60	30%	0.4855	\$392,640.00	\$88,760.64	\$0.00	\$481,400.64	£258,014.38
Solar Cooling (SFC/1h) 1h heat storage	Cooling+ Heating	55%	327.20	10%	0.5515	\$130,880.00	\$100,826.97	\$10,476.93	\$242,183.90	£129,802.34
		80%	654.40	20%	0.8030	\$261,760.00	\$146,806.99	\$10,476.93	\$419,043.93	£224,593.30
		86%	981.60	30%	0.8606	\$392,640.00	\$157,337.61	\$10,476.93	\$560,454.54	£300,384.58
Solar Cooling (SFC/3h) 3h heat storage	Cooling+ Heating	74%	327.20	10%	0.7446	\$130,880.00	\$136,130.12	\$31,446.01	\$298,456.13	£159,962.34
		98%	654.40	20%	0.9827	\$261,760.00	\$179,660.31	\$31,446.01	\$472,866.32	£253,440.27
		99%	981.60	30%	0.9917	\$392,640.00	\$181,305.72	\$31,446.01	\$605,391.73	£324,469.38

**Table 15:** Calculation showing the cost of the different solar cooling systems display in USA.

This formula for the capital cost will be applied to the four solution cases.

#### Case 1

The capital cost for case 1, which covered all the electricity loads of the building with photovoltaic panels is: **£ 2,372,659.23** with the system is installed in Colombia.

#### Case 2

Case 2 is considered as a combined system which covers 100% of electric loads and more than 70% of cooling loads using both photovoltaic and absorption cooling:

The capital cost is equal to: £159,962.34 + 1,898,127.38 = **£ 2,058,089.33**

#### Case 3

It considers 50% of the electrical loads (equipment and lighting) and more than 70% of cooling loads using both photovoltaic and absorption cooling.

Capital Cost= £ 159,962.34+ 949,063.69 = **£1,119,353.86**

#### Case 4

It considers the coverage of the cooling loads with an efficiency of more of 70% using solar absorption cooling.

Capital Cost= **£159,962.34**

### Payback period

To find out the period of time over which the money spent on the capital cost of the solar system equals the costs of the annual conventional electricity supply, we will apply the following formula:

$$\text{Payback period} = K/C$$

Where:

K = Capital cost of the solar system;

C = Annual cost of conventional electric supply as described in page 56

PAYBACK					
Case	System	Coverage	K	C	Years
1	100% PV	100% building electric demand	£2,372,659.23	£46,317.37	51.23
2	Combined	100% electric loads and cooling 74% efficiency	£2,058,089.72	£46,317.37	44.43
3	Combined	50% electric loads and cooling 74% efficiency	£1,109,026.03	£46,317.37	23.94
4	Solar Cooling	Cooling loads 74% efficiency	£159,962.34	£9,263.67	17.27

**Table 16:** Payback calculation.

The above table shows that only Case 3 and 4, at present level of cost, look like possible financially viable solutions. Under Case 3, the capital cost can be paid back in less than 24 years, whereas in Case 4 the payback period will be just over 17 years.

## Conclusions

the solar radiation. The solar radiation was obtained from the meteorological data of Medellín, Colombia, and the solar radiation was obtained from the meteorological data of Medellín, Colombia.

The study demonstrated that solar energy is a viable alternative for the city of Medellín, Colombia. The study also demonstrated that the solar radiation is a viable alternative for the city of Medellín, Colombia. The study also demonstrated that the solar radiation is a viable alternative for the city of Medellín, Colombia.

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## Conclusions

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## Conclusions

This study demonstrated that active solar energy, from a technological point of view, is a feasible energy option for the "EPM public library" in Medellín. On the other hand, the economical study demonstrates that its payback period is still too long to make it financially viable.

It is technologically feasible for the following reasons:

Due to the availability of the source during the whole year, solar energy is a perfect option that must be fully exploited.

The area of the building that best captures the solar radiation is the roof, which can be used for active solar energy purposes without affecting the constructed building and furthermore, it is the largest usable area. In the case study, the simulation showed that to satisfy the energy demand of the building, the roof area was sufficient.

Among various types of solar cooling alternatives tested, the SFC/3 was chosen because, with a smaller area, it has an efficiency higher than 70% that compensates for the cost of the additional storage tank that it requires for its operation. Furthermore, it gives better results than the photovoltaic system in order to reach the cooling loads.

These active solar systems can be applied to the constructed building with very limited additional work inside the building, thus affecting neither the internal structure nor its functionality.

In addition, after the simulation of the public library, it was demonstrated that the use of passive solar strategies helps to minimize the annual cooling loads of the building from 478,048.60 kWh to 470,992.02kWh. Consequently, the reduction of the energy consumption is 7,056.58 kWh per one year.

The active solar energy systems can produce 100% of the energy required to run satisfactorily the library, making it a sustainable building.

The study demonstrates that the use of combined systems presents better results because it can cover more demand with less area occupied by the system, requiring less initial investment. At the same time, the use of conventional energy can still be partially used in combination with solar systems. The solar cooling technology should be seen as an assisted

system, which helps considerably in reducing the annual cost of the conventional air conditioning system. In this case the amount of energy savings made by the system depends upon the correct design and choice of the right technologies and devices.

It is not financially viable at the moment because, as the economical study has demonstrated, only case C and D have a payback within the lifetime of the system and solely Case D has a reasonable payback period (17.27 years). Consequently, the other two options (case A and B) would constitute as just pilot projects. In spite of this, purely financial results should not discourage this type of technology, because other important factors have to be taken into consideration after the right system is chosen.

The cost of solar energy has a constant downwards trend, due to the technological advances and the increased demand that allows economies of scale. For example, in 1982 the cost of the photovoltaic system was \$27/Wp and today it is only around \$4/Wp. Furthermore, precisely to keep prices as low as possible, in this study, the polycrystalline panels for the photovoltaic system that give an efficiency of just 12% were used. With the scientific progress, it is reasonable to expect that systems with higher efficiency in the future will be available at lower cost.

In case the decision to have active solar energy is taken at building design level, then the cost of solar energy panels would be at least partially offset by those of the tiles of the roofing. This could represent a saving of around 20%.

The demographical aspect needs to also be taken into consideration. The findings show that Medellín's population will increase by 25% in 10 years and this will consequently affect its energy demand. At some point, the present capacity of generation will not be sufficient and new sources of energy will be needed. This will aggravate the problems associated with the complete dependency on one source of energy. The Colombian government is well aware that renewable energy resources, such as active solar energy, are the main alternatives to contribute to satisfying the demands of the Kyoto protocol.

Furthermore Colombia is on the way of signing the Free Trade Treaty (TLC) with the United States and this could mean that solar technologies in Colombia will be available at the same prices as those found at the U.S.A. This will represent a reduction of between 20% and 30% in relation to the present costs.

Therefore, experiments like the above should be encouraged because they represent a future solution to environmental problem. At this stage, the financial gap should be supported

by the government, in the forms of incentives such as tax reductions in the import products, foundations and research institutes.

To sum up, solar energy is an environmental friendly alternative to the present total dependence upon one single source of energy and above all, it is a self sustainable technology when applied to a single building. For this reason, the solar energy solution could be extended to other buildings with similar characteristics such as public offices or schools that are open when solar energy is available. This would benefit Medellín in particular and Colombia in general.



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